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FINAL PROJECT REPORT

Pipeline Right-of-Way Monitoring and Notification System

**Gavin Newsom, Governor
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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research
- Natural Gas-Related Transportation.

Pipeline Right of Way Monitoring and Notification System is the final or interim report for this project (Contract Number PIR-14-014) conducted by the Gas Technology Institute. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the [CEC's research website](http://www.energy.ca.gov/research/) (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

Natural gas is a critical energy resource that utilities must deliver to customers through safe and secure pipelines. A primary threat to gas infrastructure is encroachment by nonutility companies that cause accidental damage when excavating. A monitoring technology to notify gas utilities about activity in their pipeline rights-of-way would benefit utilities and the public by increasing safety and reducing system damage. The monitoring technology must be cost-effective and able to retrofit to existing infrastructure.

Gas Technology Institute has strong research and development experience in right-of-way monitoring. The two technologies pursued extensively include: 1) permanent attachment of vibration and other sensors at intervals along the gas pipeline (tracking what is underground) and 2) tracking the location of excavation equipment relative to the pipeline (tracking what is aboveground). The current advances in wireless, mobile, and low-power technologies allow use of these two solutions at an affordable cost.

This project installed a monitoring and notification system on an active natural gas pipeline, demonstrated the operation of the system in a remote area using solar power and wireless data collection, and monitored the results. The research team developed data records for several months of pipeline and surrounding environment conditions.

Keywords: Right-of-way monitoring, encroachment detection, excavation encroachment notification, third-party damage, safety, monitoring, gas pipelines, risk management

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EXECUTIVE SUMMARY

Introduction

There are 215,000 miles of gas pipelines in California with roughly 12,000 miles of high-pressure gas transmission lines. The greatest threat to buried natural pipelines is the operation of nonutility company excavation equipment within the pipeline legal right-of-way, resulting in accidental damage. Damage to the pipeline can have severe safety consequences, including fire, explosion, and loss of life. Pipeline damage can also lead to natural gas leaks thereby increasing greenhouse gas emissions, and disruption of natural gas delivery to customers. A system that could provide advanced notice of potentially damaging activities would benefit gas utility operators as well as the public at large.

The proximity of pipelines to populated areas is a critical consideration when designing a monitoring system. Natural gas utilities have developed a risk classification system where risk is calculated as the probability of pipeline damage multiplied by the severity of the consequences. The more populated the area, the higher the assigned risk value. The term "high consequence areas" applies to locations where the public is near the pipeline right-of-way.

Current methods to comprehensively monitor the right-of-way, such as distributed fiber optic sensors, require exposing the entire length of the pipe for installation. In dense, urban areas this "open trench" installation is logistically difficult and expensive. Open trench activities also create risks for workers and the public independent of pipeline damage. Despite challenging logistics, a high consequence area would also benefit most from right-of-way monitoring because of the inherent, enhanced risk of its location. Given these conditions, finding a technological solution that is both affordable and effective is key.

Project Purpose

This project designed, tested, and demonstrated in the field a system that automatically monitors the right-of-way and notifies gas utility operators of encroachment threats. The use of this system will allow utilities to mitigate risk to their pipelines by knowing where and when threats are occurring. The current practice is for utility inspectors to patrol the right-of-way with emphasis on areas where construction is known to be ongoing. Automated monitoring and notification will allow these personnel to be more efficiently dispatched.

Project Approach

This project demonstrated a monitoring system where sensor stations were placed at several discrete locations in the right-of-way. These stations consisted of sensors on the pipe and in the soil, a data logger, and a wireless link to forward the data to a central repository. The two most important considerations for this approach were designing an affordable and effective system. While affordability is key to market adoption, the system must also successfully identify encroachment threats to bring value to utilities, ratepayers, and the public. To address affordability, the project team identified how far apart the sensor stations could be spaced and remain effective. This allows the system to operate while minimizing equipment and excavation costs. The project also focused on using low-power equipment. It is expensive to bring alternating current power into gas utility installations, even when they are in urban

settings; in rural settings it may not be possible. An acceptable system needs to operate from battery or solar power.

Once the system is put into place and collecting data, it must be communicated to the utility through an easy to understand user interface or “dashboard”. The interface needs to have the ability to relate right-of-way encroachment events and notifications to specific locations on the infrastructure critical to the utilities.

With these utility operator considerations built into the approach, the project team selected a variety of suitable components for monitoring activity in the right-of-way as well as hardware to construct a field-ready monitoring station. Full details of each of the components can be found in this report.

In summary, the approach was designed to provide the widest monitoring of the right-of-way at a reasonable cost. The approach addresses equipment, installation, and maintenance costs. It also addresses the operation costs of responding to notifications by intelligently filtering the data to identify actionable threats in the ROW.

Project Results

This project successfully designed, engineered, and tested in the field a natural gas pipeline right-of-way monitoring system. Various sensor types were installed and tested, and the pipeline was hydrotested during the installation, capturing calibration data. Support electronics were installed, and a solar power option was successfully demonstrated. The wireless link technology was successful. Three sensor stations were installed over roughly 4,000 feet of new pipeline. The system is currently running and providing sensor data. The web hosted user interface was successful. A user interface dashboard was demonstrated that allows visualization of the data from the three sensor stations. Alerts can be generated based on the data received wirelessly. The dashboard is currently running and available to the utility hosting the test site. This testing highlighted several key findings:

1. Overall the monitoring system performed successfully and as designed. Communication links between the stationary sensors, mobile sensors, dataloggers, weblinks, and user dashboard were all established. It was possible for a user to “see” a pipeline right-of-way, the surrounding environment, and the locations and status of the sensors in real-time.
2. Further refinement is necessary for the vibration sensors. While most tested sensors were able to effectively identify impacts, the performance of the stationary vibration sensing equipment was poor. During field testing, data from these sensors initially failed to register the activity of an excavator and a soil compactor. These activities provided data needed to adjust the sensitivity and scaling factors for the vibration sensors. The performance of the vibration sensing system was improved during these tests. While further work is necessary, the basic functionality has been demonstrated.
3. Maximum distance range between stationary sensors was identified. The project team placed the three sensor stations between 2,000 and 3,000 feet apart, which proved to be a largely effective spacing. Further refinement of this distance can be determined in future work.

4. A right-of-way monitoring system can be a net-positive investment. The project team gathered cost information during this system design process, as well as utility input on typical costs for pipeline excavation and cost figures from past damage incidents. The right-of-way monitor system offered a variety of economic, safety, and environmental benefits. The team estimates that installing a second-generation right-of-way monitor system on 10 percent of California gas transmission lines (1,239 miles) will require an investment of more than \$30.5 million, with benefits that include 0.76 fatalities avoided, 4.4 injuries avoided, 29,516 thousand cubic feet (MCF) of methane emissions avoided, and \$38.9 million in avoided costs. These estimates used conservative assumptions and economies of scale from a large roll-out that are expected to further reduce monitoring system hardware costs.

Technology and Knowledge Transfer

There are several avenues for future use and commercialization of the right-of-way monitoring system. However, securing a test site and the initial installation required considerably more time than planned. The initial technology transfer plans assumed nine to twelve months of testing would be accomplished on an operating pipeline and the information presented to several industry forums. Various delays led to the system testing being compressed into the last three months of the project, affecting the technology transfer activities. The work has not been presented at a public industry forum yet.

Operations Technology Development, LLC observed and provided additional financial support for this project. Operations Technology Development is a research consortium that includes all 26 of the major gas utilities in the continental United States. Southern California Gas, Pacific Gas and Electric, and Southwest Gas are members. Gas Technology Institute has face-to-face meetings with the Operations Technology Development membership twice per year, and members received quarterly reports on this work. Several non-California members expressed interest in hosting test sites pending results of this project. The interaction between Gas Technology Institute and Operations Technology Development provided knowledge transfer to an industry group that contains the greatest number of potential right-of-way monitor adopters.

Trilliant is a provider of wireless data communication hardware and services for utilities and "smart cities." Trilliant currently holds the intellectual property for the random phase multiple access radio system. This system provides significant advantages in terms of radio range and efficiency. A small number of "towers" can cover a large geographic area, making the system more economical than cellular and similar systems. Trilliant has expressed an interest in the right-of-way monitoring technology as a path to greater market adoption for the wireless technology and are interested in expanding the demonstration to additional sites.

Benefits to California

The primary benefit is public safety by preventing damage to pipelines and associated incidents. There have been several instances of construction equipment striking buried gas lines resulting in pipe ruptures and fires. The Bakersfield incident of 2015 is one such instance, which fortunately occurred in a rural rather than urban setting. One major incident cost more than \$600 million to remedy. This cost (which is not final) is in addition to injury and loss of life. While the root cause was not excavation related, it demonstrates the scale of

consequences when an incident occurs in a populated area. Such an incident might have been avoided with the pipeline monitoring technology developed by this project.

Based on economic analyses prepared for this project, installing a second-generation right-of-way monitor system on 10 percent of California gas transmission lines (1,239 miles) would require an investment of more than \$30.5 million.

With a full 10-year use plan, it is likely that economies of scale can drive the hardware costs lower. This will not affect the excavation costs but will provide more margin to install the system in more challenging locations while still maintaining the cost effectiveness.

A right-of-way monitoring system that is too expensive to install will benefit no one, regardless of how effective it is. By developing technology to retrofit the right-of-way monitor system one excavation at a time, this project has shown the practicality for utility operators and can be used when necessary where critical pipelines and population intersect.

CHAPTER 1:

Introduction

Background

Several recent pipeline incidents (Figure 1) have raised public awareness of natural gas pipelines and infrastructure running underneath developed areas. What were farm fields when that infrastructure was first installed, decades ago, are now subdivisions. Even though the infrastructure is sound and well-maintained, its proximity to population raises the consequences of any failure, elevating risk. It is important to note the acceptable cost of monitoring has steadily risen over the past several decades. A U.S Department of Transportation research solicitation from the early 1990's indicated that the utility willingness to pay for monitoring was roughly \$2,000 per mile. The 2015 California Energy Commission solicitation that resulted in this project set the value closer to \$100,000 per mile. This metric recognizes that while the probability of a pipeline failure is low, the associated consequences can be high. Investing in a monitoring system can be effective insurance against the cost of dealing with a catastrophic incident.

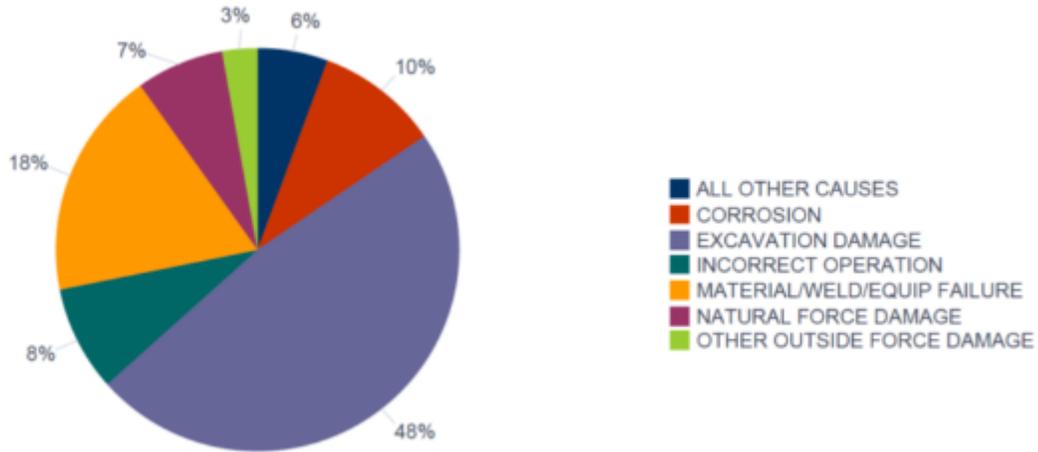
Figure 1: Bakersfield Pipeline Dig-in Incident



Source: PG&E

The primary threat to buried infrastructure is excavation and/or construction damage. This is indicated by statistics gathered by the Pipeline Hazardous and Material Safety Administration (PHMSA) of the United States Department of Transportation (US-DOT). The threat can be from utility owned equipment, contractor equipment, or private citizens performing activities not related to the utility (Figure 2).

Figure 2: Sources of Damage Leading to Incidents



Source: PHMSA Pipeline Incident 20 Year Trends <https://www.phmsa.dot.gov/data-and-statistics/pipeline/pipeline-incident-20-year-trends>

Detecting the presence of excavators or construction equipment in the pipeline right-of-way (ROW) would allow operators to quickly dispatch personnel to investigate and forestall potential damage. Early and preemptive action would substantially mitigate the risk of a pipeline incident.

This project explored several approaches that could be used in combination to reduce third party excavation damage:

1. Through a Global Positioning System-based Excavation Encroachment Notification (EEN) technology that tracks the location and status of excavation equipment.
2. Through the development of a Stationary Sensor Network (SSN) that monitors parameters at several locations on a pipeline.
3. Through the development of advanced geospatially-based analytics that can accept multiple streams of data and extract events of interest from background noise.

These approaches all make use of the Global Positioning System (GPS). This technology has allowed investor owned utilities (IOU) to significantly improve the accuracy of their infrastructure maps. This has in turn, driven the adoption of Geographic Information Systems (GIS) to house utility data. GIS technology is being used with cellular-connected sensors placed on construction equipment to track their movements in real-time. Real-time tracking of construction equipment, gas system infrastructure GIS data, and activity characterization algorithms are used to alert the utility to potential damage from active excavations. Accurate location of the infrastructure, the detected threats, and the responding personnel is foundational to the analytics.

An example of location driven monitoring and response is the EEN technology developed by GTI. This technology utilizes commercial off the shelf software from Esri. A device is placed on construction equipment to stream GPS and other sensor related data via the cellular network to the utility. This allows the utility to know where construction equipment is located, if it is active, and what it is doing (digging, idling, moving locations).

The SSN approach monitors specific locations within the ROW. A series of fixed sensor stations are installed along a pipeline to perform 24/7 monitoring. An advantage of the SSN approach is that, unlike the EEN technology that must be placed on the construction equipment, it monitors the pipeline infrastructure itself. It may be difficult for the utility to know when third party construction equipment was going to be working within their ROW, and the costs and logistics of installing monitors on third party equipment may also present a challenge.

The analytical approach uses Esri software to access data streams from both the EEN and SSN devices. A detailed and user-friendly interface provides utility operators with a clear picture of the circumstances and activities on the ground. Analytics will alert utility operators if individual EEN or SSN devices are indicating alarm conditions – if an encroachment on the pipeline ROW looks imminent. A great advantage of central analytics is that they provide a detailed view of the monitored area. If a single SSN device indicates activity in the ROW, data from other sensors in the vicinity can be examined. These neighboring sensors may provide trends or supporting data that assist in determining if a threat is present.

Project Goals

The goals of this project are to demonstrate ROW monitoring by:

- Using a sensor-based system to detect threats entering the ROW
- Demonstrating the wireless collection of threat data to a hosted repository
- Demonstrating analytics that can identify actionable threats from the data
- Providing wireless notification of the identified threats to appropriate parties

The system must collect observations of multiple attributes at multiple locations within the ROW to form a detailed overall picture of pipeline status. Figure 3 lists attributes the demonstration system will monitor. It is important to understand that more than one of these influences may be active at a given time and that circumstances other than construction activity can cause pipeline damage.

Figure 3: Overlapping Influences in the Pipeline ROW



Source: GTI

Value to Utility Operators

The primary value of the monitoring system is to provide utility operators a clear view of potential developing threats to their pipeline in real-time, enabling them to proactively respond to mitigate damage or risk. In addition to improving safety, energy supply, and pipeline infrastructure, this will reduce costs related to accidents. Of the 215,000 miles of gas pipeline in California, roughly 12,000 miles are high pressure gas transmission line. The cost of averting even a single San Bruno-scale incident would provide \$50,000 per mile to invest in monitoring these lines.

CHAPTER 2:

Right-of-Way Hardware Design Approach

Monitoring activity in the pipeline ROW, with an emphasis on excavation and construction activity, will allow utility operators to react to threats more quickly and mitigate risk to the pipeline and surrounding area. A system architecture was developed to provide continuous monitoring of the pipeline ROW. This chapter provides a high-level view of the technologies selected for this purpose.

Requirements

There is a large existing network of pipeline, totaling about 215,000 miles in California. A practical monitoring system must work for new and existing pipe and excavation equipment. To keep installation costs low, it is important that the footprint of the equipment attached to the pipe itself is small and done with minimal excavation, preferably in a keyhole opening. GTI elected to use “point” sensors installed on the pipeline at regular intervals to meet these needs. Distributed sensors, such as those based on fiber optics, can provide good coverage and localization of problems but require trenching to install. While distributed sensors may be appropriate for new construction, they are problematic for retrofit situations. Figure 4 shows the above ground portion of an actual sensor installation.

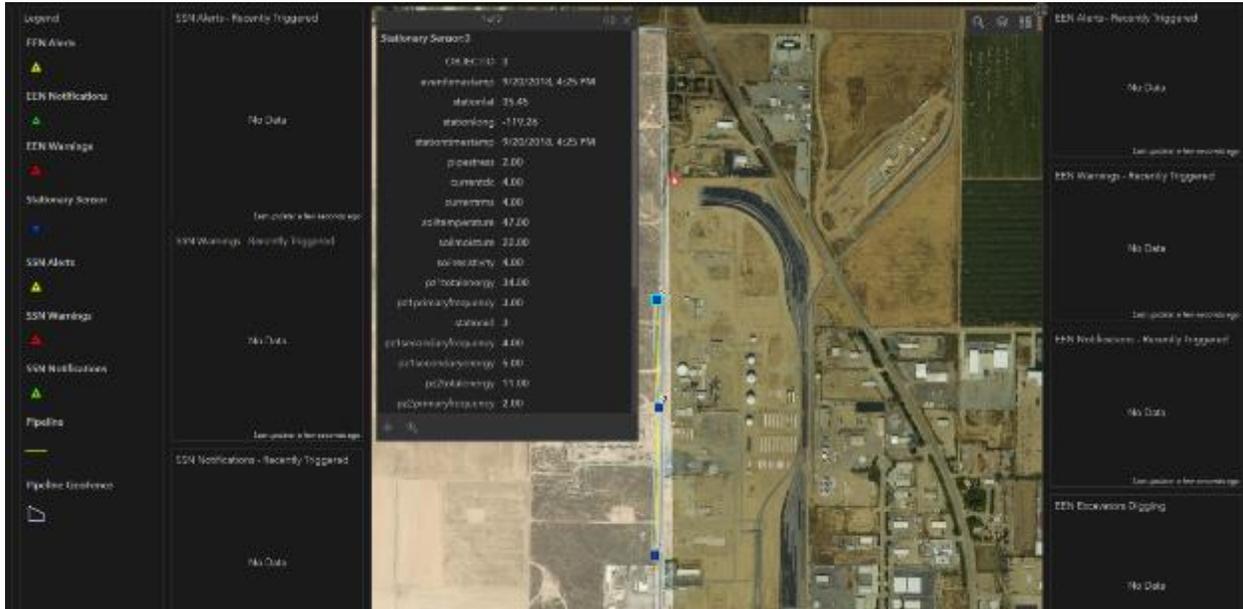
Figure 4: Completed Sensor Station



Source: GTI

To be effective, the analytics portion of the system must filter data in such a fashion as to not overwhelm utility personnel unnecessarily. Figure 5 shows a sample version of the operator dashboard for viewing multiple sensor data feeds, providing an overall view of pipeline status.

Figure 5: Dashboard for Right-of-Way Monitoring Concept



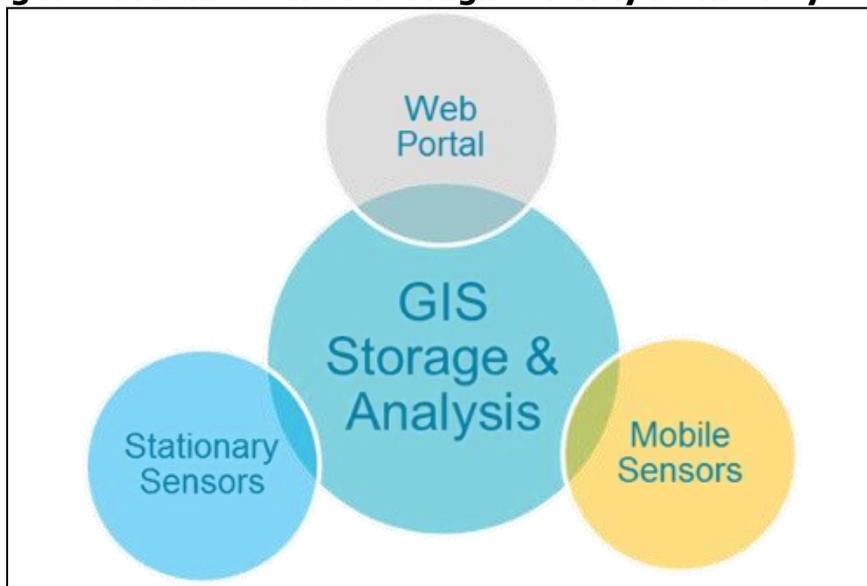
Source: GTI

System Architecture

There are four distinct components that comprise the system architecture, as seen in Figure 6.

1. A central, GIS-based repository that can store and analyze data.
2. A set of stationary pipeline sensors that transmit data to the repository.
3. A set of mobile sensors on excavation equipment that transmit data to the repository.
4. A web portal or user “dashboard” that provides the end users with alerts and visualizations of conditions on the pipeline ROW.

Figure 6: Architecture for a Right-of-Way Monitor System



Source: GTI

The goal of continuous monitoring is to provide utility operators warning of activity in the ROW before the pipeline is struck. This was achieved by placing multiple sensors on the pipeline and in the adjacent soil, which have wireless connectivity to a central data repository. This architecture allows the total data across multiple sensors to be analyzed simultaneously in real-time.

Multiple sensor locations along the pipeline provide a more resilient system by allowing users to understand and differentiate between local and global events on the pipeline. An example would be a heavy thunderstorm versus local digging. Weather events would excite all the appropriate sensors on a pipeline at the same time, whereas digging activity would be localized to one area. Analytics would serve as the “brains” of the monitoring system and interpret the localized sensor results to provide operators with appropriate alerts, instead of flooding utility operators with alerts during a routine global event, like a heavy thunderstorm.

The backbone of the system is wireless connectivity of these distributed sensors to a centralized data repository. Wireless connectivity for the stationary sensors was provided by random phase multiple access (RPMA) radios that provide long range and low power. The data was hosted on a cloud platform that can also perform the analytics is required. The aggregated and hosted data were available to the utilities through a web-hosted dashboard and specific alerts were distributed to designated personnel via email or SMS channels.

In conjunction with the stationary pipeline sensors, mobile sensors were installed on excavation equipment. This allowed the location and equipment status to be monitored in real-time. When excavating equipment crossed a “geo-fence” around a known pipeline or utility asset, an alert was generated that also contains the status of the equipment. The sensors on the excavator could estimate if the device is digging or just passing through.

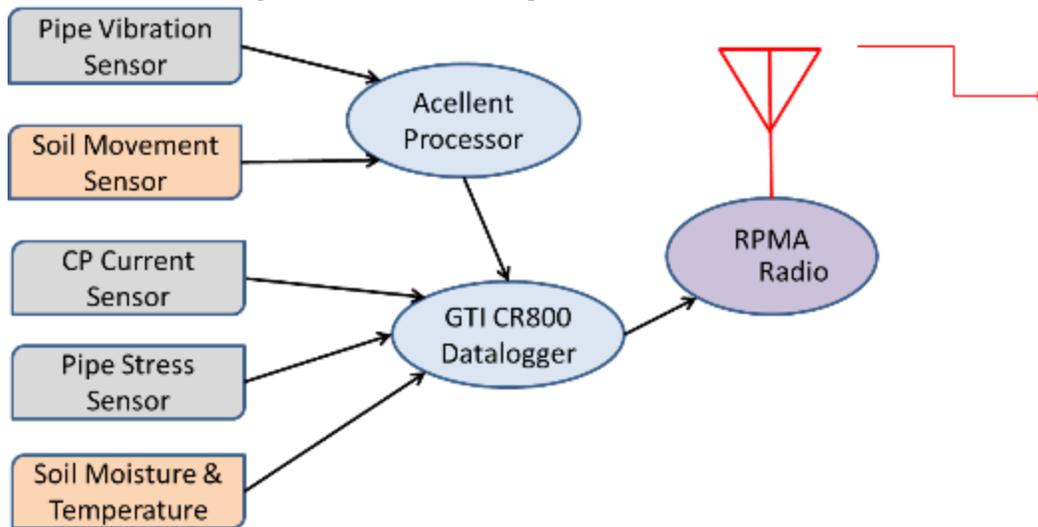
Stationary Sensors for Right-of-Way Monitoring

With the high-level architecture defined, next the hardware required to provide the appropriate data feeds was selected. To select the correct hardware, the project team identified the key environmental parameters that needed to be monitored. Data about the vibration level on the pipe, the tensile stress and the cathodic protection current were captured. These parameters were selected because their effects can travel for long distances in the steel of the pipeline. Impacts on or near the pipe can cause vibration travelling thousands of feet. Disturbances such as landslides or settlement that deform the pipe cause stresses that can be extend for sizable distances. Cathodic protection currents travel for miles in the pipe metal; changes in current can indicate breaks in the coating or other problems. This hardware consists of the following sensors placed onto the pipe or in the adjacent soil (Figure 7):

- Soil Seismic Sensor
- Soil Moisture and Temperature
- Current Density Coupon
- Pipe Strain Sensor
- Pipe Vibration Sensor

Each station also requires electronics to process the sensor signals, a means to log the data, and a radio to forward the data to the central storage location.

Figure 7: Stationary Node Architecture

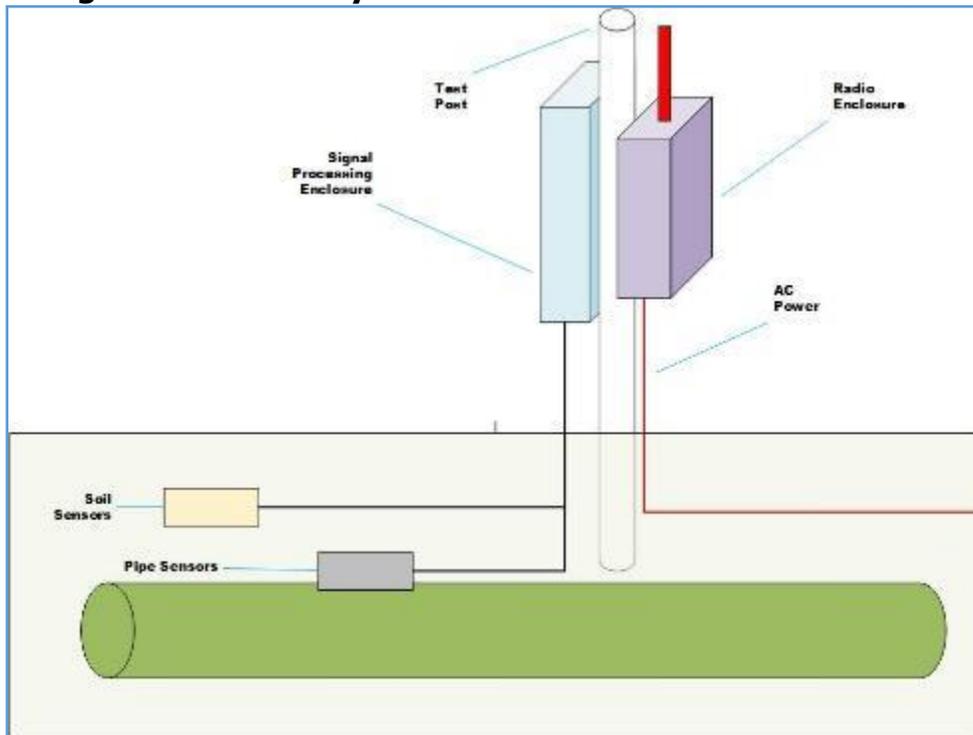


Source: GTI

These sensors will respond to activities other than excavation. Seismic activity would affect the pipe vibration sensor and the soil movement sensor simultaneously. Drastic increases in soil moisture or temperature can change the strain level in the pipe. Neither of these scenarios are caused by digging equipment near or in contact with the pipe. However, as monitoring for these types of activities was outside the scope of this project, the addition of further sensors to the soil to discriminate between these activities was not implemented at this time.

The sensor stations are placed at multiple locations along the pipe, roughly 2,000 to 3,000 feet apart. Figure 8 shows a conceptual installation diagram using a stationary sensor station post. Test station posts are a common utility tool used to house wiring and as mounting place for instrumentation. In this view, the signal processing electronics and the radio equipment are housed in separate enclosures. The various sensors are below ground with wiring leading to the signal processing electronics. Power is shown as being brought in below ground. The schematic view provides one possible installation arrangement and is not intended to be prescriptive.

Figure 8: Stationary Sensor Installation Schematic View

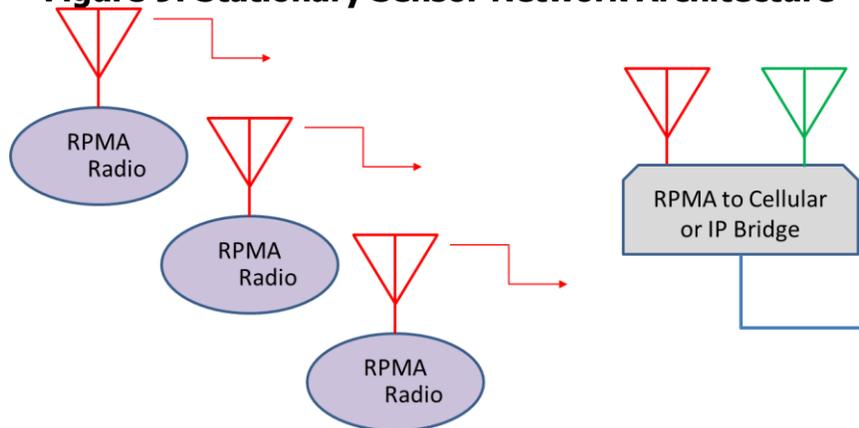


Source: GTI

Wireless Sensor Communication

Data from all the stations (Figure 9) was wirelessly transported back to a central location via an access point that serves as a bridge to the internet.

Figure 9: Stationary Sensor Network Architecture



Access points acted as a bridge between the RPMA radios and the Internet. One access point bridge can serve thousands of the RPMA radio nodes; the intention for this project is to provide 10 sensor nodes and two access points for each test site. The range of the RPMA radios can be several kilometers depending on the obstructions in the path. Figure 10 shows a rooftop installation of the RPMA access point bridge with a solar power supply.

Figure 10: Typical Installation for Random Phase Multiple Access Point



Source: Leidos Engineering

Each stationary sensor installation will require one of the “Canary” RPMA radios mounted above ground (Figure 11) to provide communications to the nearest access point bridge from RPMA to IP. The access point is shared among all the stationary sensors within several kilometers.

Figure 11: Close-Up of Canary Radio on a Test Post



Source: Leidos Engineering

Mobile Sensors for Right-of-Way Monitoring

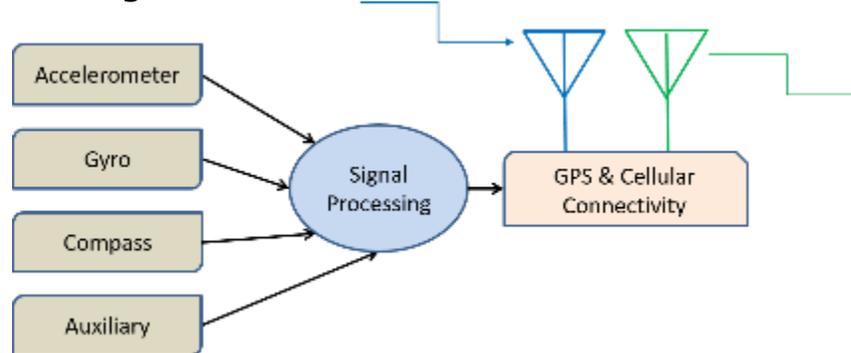
The objective of the mobile aspect of the project is to provide real-time alerts of ROW activity based on monitoring vehicles’ position relative to the ROW. EEN devices equipped with motion and location sensors are mounted on a vehicle and monitors its activities. The sensors provided by the EEN devices are:

- GPS location and heading
- 3D accelerometer and gyroscope

- 3D magnetometer/compass

The GPS aspect of these devices allows alerts from multiple locations to be correlated and sent to utility operators through a web-based interface “dashboard”. The mobile devices communicate with a data aggregating server through a cellular modem. Figure 12 illustrates the EEN mobile sensor architecture. It consists of onboard sensors, a signal processing unit and a cellular modem. All are packed into an enclosure with interfaces to vehicle 12-volt power and to an external GPS antenna.

Figure 12: Mobile Sensor Node Architecture



Source: GTI

Mobile Sensor Communication

Mobile ROW devices are equipped with an onboard cellular radio. Connectivity is enabled through a SIM card and data subscription plan. Each device has a unique serial number, which enables multiple devices to communicate to the same host repository with unique identifier. The reported data can be correlated with the stationary data in that area and produce a reliable alert stemming both from a geographic location (a geo-fence) and mutual dynamic readings. The current version of the EEN device also provides an audible alert to the vehicle operator when the geo-fence is crossed.

CHAPTER 3:

Communication System Design

For a ROW monitoring system to be widely adopted, its wireless communication system needs to combine the attributes of low-power, low-cost, and long range. It must be capable of running from battery or solar power, avoiding the need to bring in AC mains power to every possible sensor location. Low-cost, in this context, refers to hardware and operating cost. Each sensor node must have an extremely low or no monthly fee. Long-range capabilities are also an economic driver, in that it can help minimize the number of sensor nodes and access points that need to be deployed to provide adequate coverage of the ROW.

The technology chosen for this project is RPMA wireless. It is a fundamentally new technology designed to dramatically minimize total cost of ownership (TCO) while providing high link capability. RPMA has profound advantages in the key performance metrics of coverage and capacity, which allows for fewer access points, with much higher capability than any other public network approach. The RPMA hardware (Figure 13) consists of multiple end-points that transfer to an access point. The access point is also a bridge to the internet through a hard-wire or cellular link. Under good conditions, an end point can be several miles from the associated access point.

Figure 13: Random Phase Multiple Access Network Hardware



Source: Leidos Engineering

Key Attributes for Sensor Networks

To effectively provide wireless connections for remote sensor nodes, a wireless technology must provide the following attributes. These attributes were considered during the selection of RPMA for this work but are applicable to any application that involves many sensor nodes.

- **Low Power/Long Battery Life.** Most endpoints benefiting from low-cost connectivity do not have access to electric power and the option of wiring power to these devices is too expensive. Changing the batteries after a few years can be a considerable expense for devices that are extremely numerous. Technologies that able support 10-20 years on

battery will represent a significant TCO savings relative to those technologies that cannot support such a battery life.

- Long Range. The range of the radio link has a direct impact on the cost. Longer range will require fewer access points or “towers” to gather the data. RPMA typically provides 3-4 km of range in urban areas and can be as much as 20 km in the absence of obstacles.
- Low Network Cost (Basic Coverage). To build a public (non-cellular) network business, a new network must be built with enough coverage for all existing and future endpoints. The capital investment required to build this network primarily depends on the amount of wireless infrastructure required. A technology that minimizes the amount of infrastructure to provide coverage is essential to make the initial capital investment feasible.

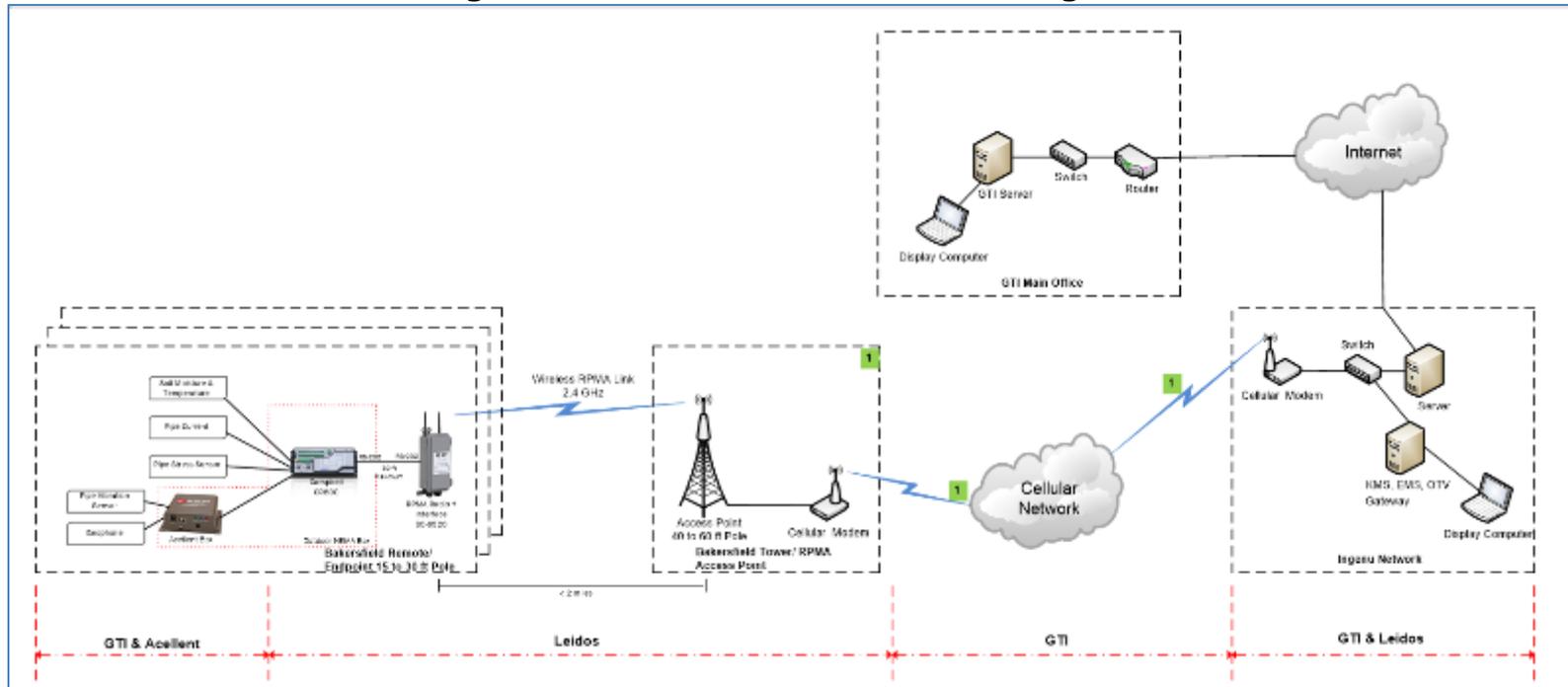
There are additional attributes that contribute to lowering the cost of wireless data collection:

- High Capacity per Network Access Point. A successful business will involve maximizing the number of endpoints that are supported by the network without exceeding capacity. A figure of merit to understand the business result is network cost per endpoint.
- Cost Effective Capacity Scaling. What happens when the capacity of a network access point is exceeded? The answer depends on the technology whether this is an easily mitigated problem or a potentially disastrous scenario. Understanding capacity scalability is critical.
- Low/Free Spectrum Cost. The cost of licensed radio spectrum is potentially very large – in the millions of dollars. Even though voice and data subscription fees can justify the spectrum expense for public carriers, the lower value endpoints typically cannot. That is why the ability to use free spectrum is a critical attribute of a candidate approach if a parallel network is being built.
- Low Endpoint Cost. Millions of communication modules certainly add up to significant cost. A networking technology to address billions of devices must be inexpensive to be feasible. However, low endpoint cost alone is not the only contributing factor to keeping TCO low.

Communications Network Design

Figure 14 shows the building blocks of the RPMA wireless system, including the sensors and how each building block will be interconnected on the network. The hardware components were commercial, off-the-shelf devices. Each building block shows the main components or elements on the block diagram. Three stationary endpoints were connected the access point. The access points used a cellular link as the backbone to send the collected data to the main office. This pilot network transferred data from the stationary endpoints to the main office for collection and visualization.

Figure 14: Communication Network Diagram



Source: Leidos Engineering

CHAPTER 4:

Data Analytics Architecture

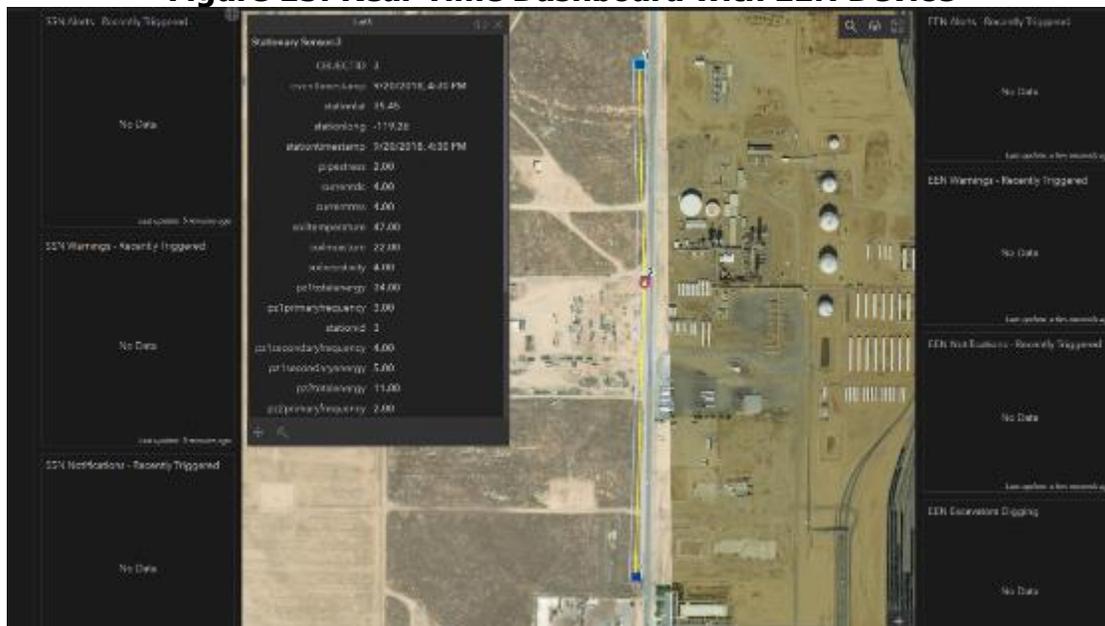
The primary driver for this project is the increased risk of incidents from damage to buried natural gas pipeline infrastructure. The damage is often related to scheduled construction activities. Operators have tracked construction activity through work permits, one-call tickets, and utility inspectors patrolling the pipeline ROW. These are administrative controls rather than engineering safeguards, which require diligence by multiple organizations to work. Even when all these steps are followed, notification of ROW activity can be late or incomplete.

An engineered monitoring system that automates notifications and alerts of ROW activity would enhance real-time operator knowledge. The automation must include analysis to accurately identify events that truly require attention amidst normal background activities. The analytics must be tuned to the specific local conditions where the sensors are installed so they do not produce false positives. An alert system that overwhelms operators with too many notifications is not useful; it quickly becomes ignored.

Data Visualization

Monitored data must be processed and presented to utility operators in a simple and easy to understand way. A web-based dashboard for utility operators built on the Esri GeoEvent Processor platform was used to visualize the data (Figure 15).

Figure 15: Real-Time Dashboard with EEN Device

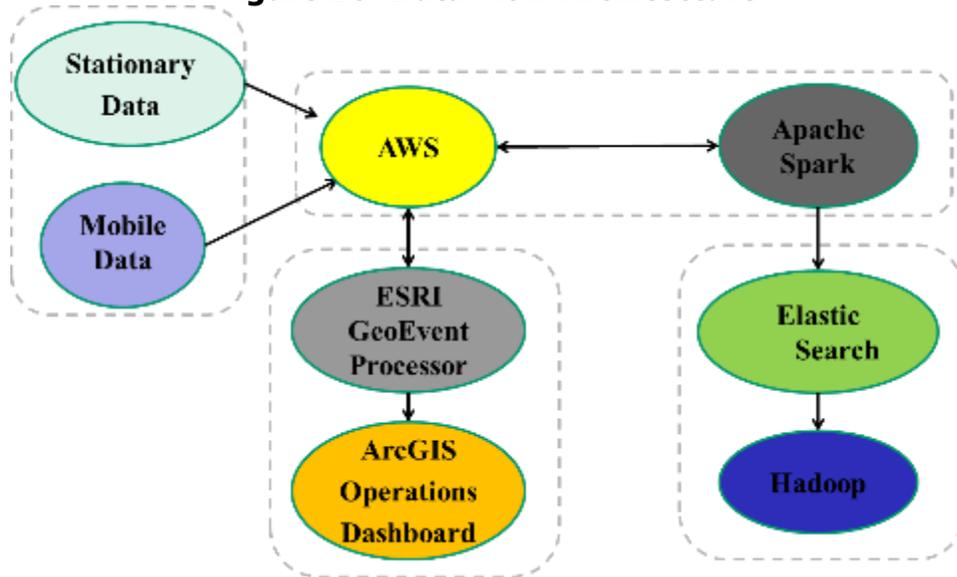


Source: GTI

There are multiple technologies that must run in the background in order to support a seamless dashboard (Figure 16). The stationary and mobile sensors have wireless connections to carry their data to a server. The raw data needs formatting prior to display; the formatting functions are hosted on Amazon Web Services which provides temporary storage and

processing capacity. For immediate display, the data is then passed to Esri GeoEvent Processor, which determines if an alarm condition is in effect. The data is then passed to ArcGIS Operations Dashboard for visualization.

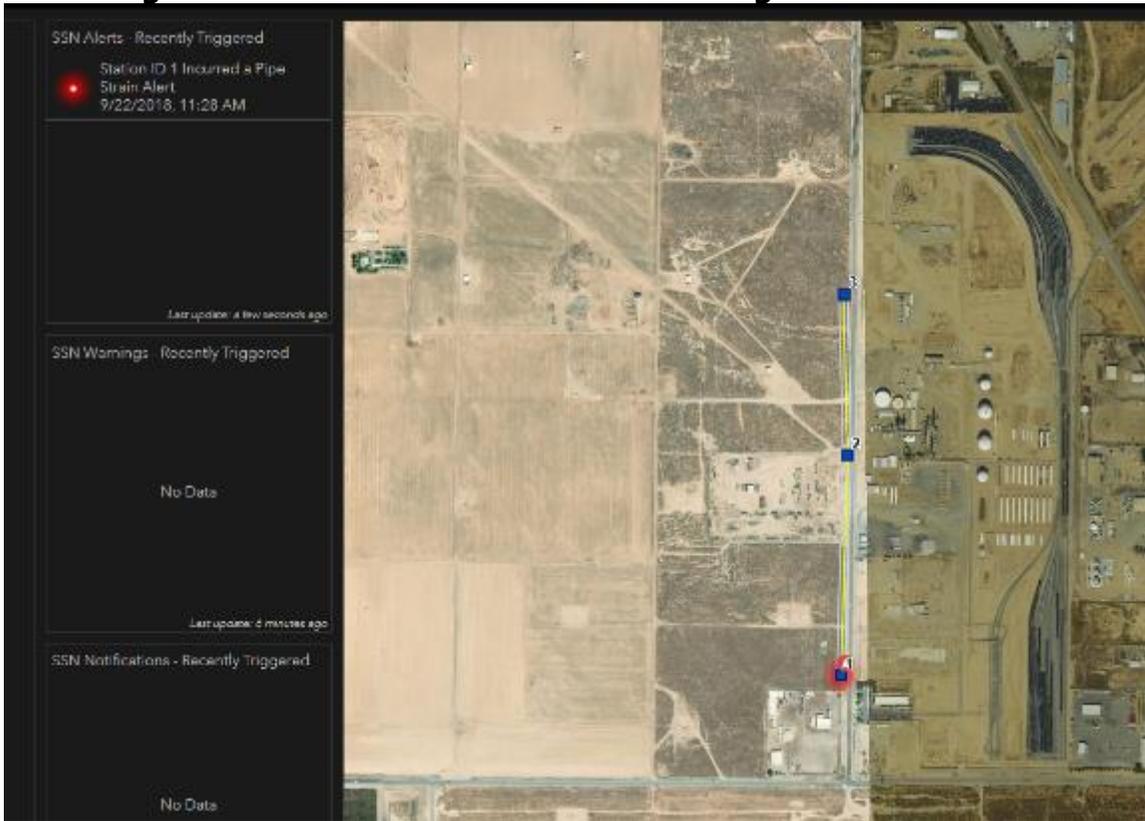
Figure 16: Data Flow Architecture



Source: GTI

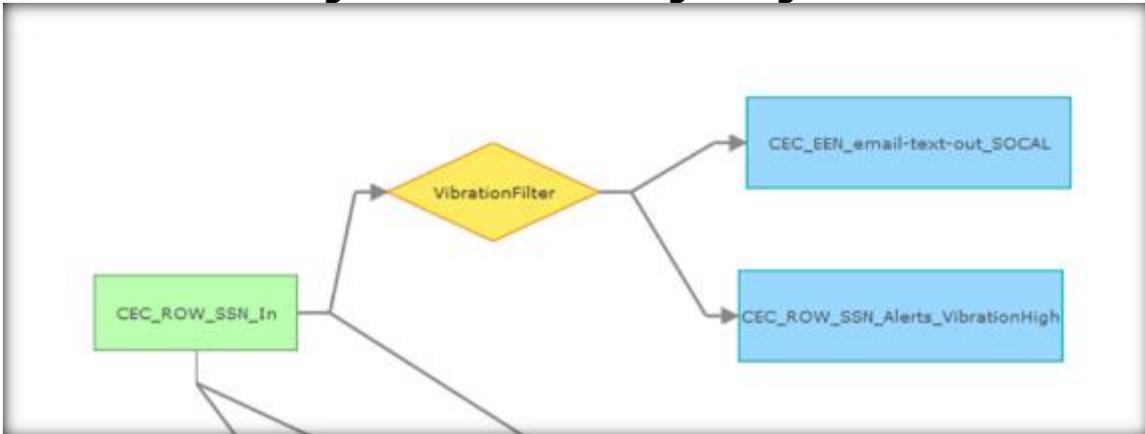
Incoming sensor readings are compared to threshold values for each of the monitored environmental parameters; if crossed, an alert appears in the dashboard both as a visual on the map and as descriptive text (Figure 17). GeoEvent processor provides a graphical programming environment to define alarm parameters and set thresholds. The programming flow shows vibration data from the stationary sensor network being passed through a filter to determine its severity and who needs to be notified (Figure 18). Notifications can be sent to the user dashboard and email or SMS messages can be sent.

Figure 17: Real-Time Dashboard showing SSN Strain Alert



Source: GTI

Figure 18: GeoEvent Logic Diagram

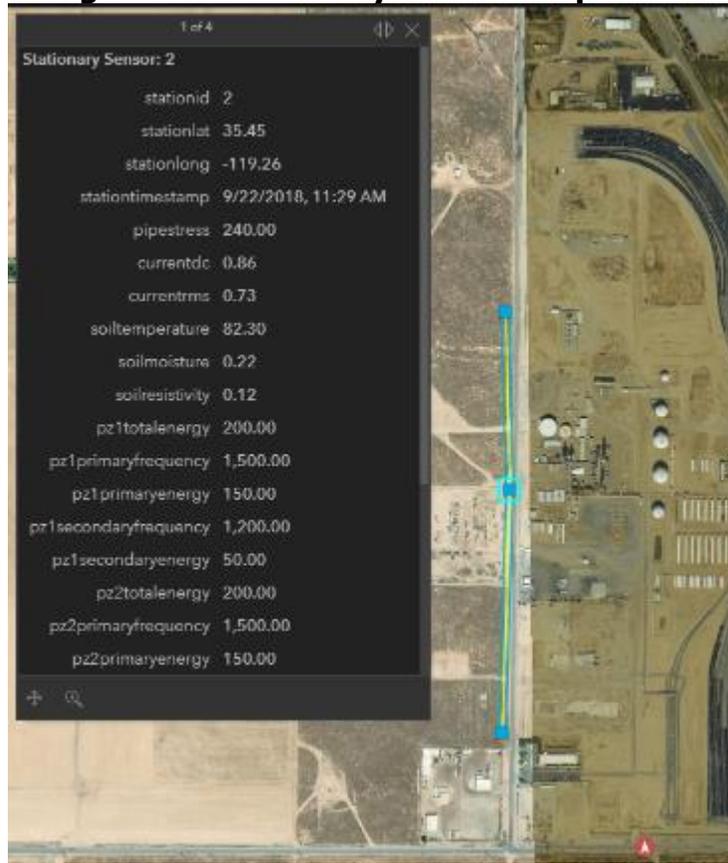


Source: GTI

Web Hosted User Interface Features

The web hosted user interface supports several modes of providing data. In the dashboard visualization, drop down displays are available to provide the most recent data associated with a stationary or mobile sensor. Figure 19 shows the data associated with a stationary sensor node on the test site. The stationary sensor nodes are represented by the blue squares along the pipeline. The middle sensor node is selected for viewing, as indicated by the square highlighting it. There is also a vehicle with a GPS EEN device visible in the lower right corner of the figure. EEN devices are represented as triangles.

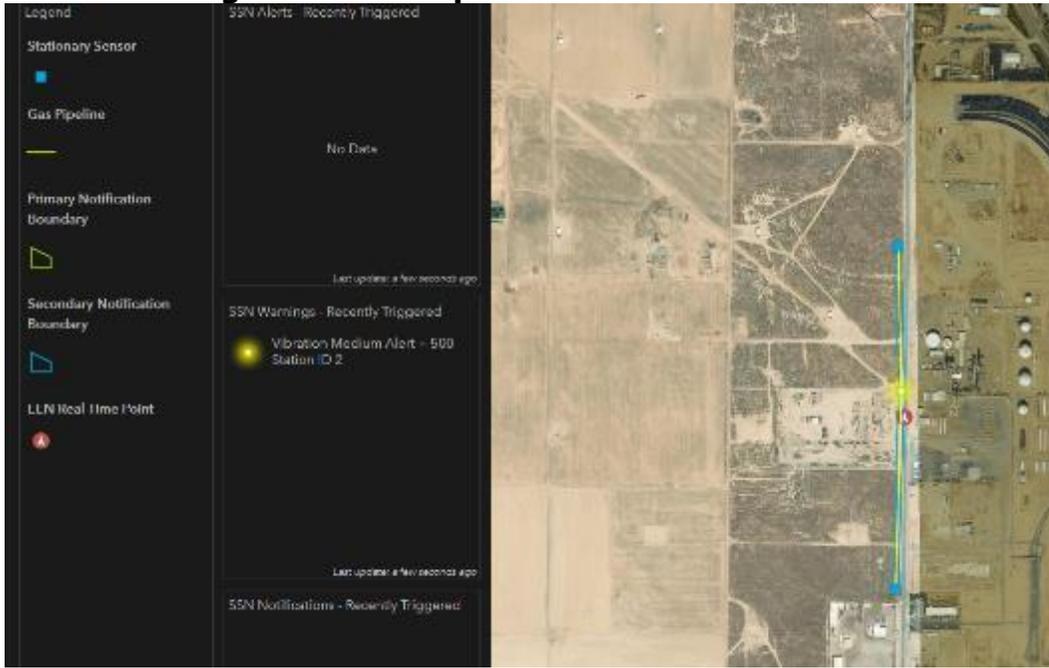
Figure 19: Stationary Sensor Drop Down



Source: GTI

Within GeoEvent Processor, it is possible to set several levels of notification relative to sensor parameters. Under this project two levels of notification were used – warning and alert. A warning was issued through the dashboard if a sensor value was approaching (but had not yet exceeded) an unacceptable level, allowing personnel to take preemptive action (Figure 20). An alert was issued when a sensor value crossed the threshold into an unacceptable range (Figure 21).

Figure 20: Example of Intermediate Alarm



Source: GTI

Figure 21: Example Email Alert

From: gti.demo99@gmail.com <gti.demo99@gmail.com>
Sent: Wednesday, September 26, 2018 9:37 AM
To: gti.demo99@gmail.com <gti.demo99@gmail.com>
Subject: Station ID 2 has Vibration Notification

Station ID 2 has Medium Vibration of **500.0**
This activity happened at Latitude: 35.44702, Longitude: -119.26123 occurring @ Sat Sep 22 16:28:35 UTC 2018.

Source: GTI

These features were demonstrated for the utility hosting the site and the wireless technology provider. Live data feeds were not available at the time of the demo. Actual sensor data that had been recorded on the site was used to exercise the features of the dashboard and the alert system.

CHAPTER 5:

Monitor Prototype Construction

The pipeline ROW monitoring system ultimately depends on data captured by sensors in the field. This chapter provides a detailed discussion the physical hardware required to capture the appropriate data (an overview was provided in Chapter 2, for reference).

Stationary Sensors

As noted earlier the sensors required to monitor conditions on the ROW need to capture data both from the pipeline and from the surrounding soil environment are the following. The specific equipment selections will be examined in detail.

- Soil Seismic Sensor
- Soil Moisture and Temperature
- Current Density Coupon
- Pipe Strain Sensor
- Pipe Vibration Sensor

The Soil Seismic Sensor is the GS-30CT geophone (Figure 22). An enclosed geophone is mounted on a spike and buried to provide good coupling with the soil. The preferred output type is digital but getting the appropriate resolution will require amplification of an analog signal with post processing.

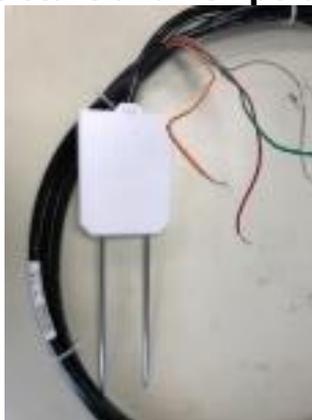
Figure 22: Soil Seismic Sensor



Source: GTI

The soil moisture, soil conductivity, and temperature sensor is the Campbell Scientific CS655 (Figure 23). This is a three-function sensor that make use of the SDI-12 standard for communication. The moisture sensor measures the dielectric constant of the soil and derives the volume moisture content through calculation. The temperature and soil conductivity are also acquired through this sensor.

Figure 23: Soil Moisture and Temperature Sensor

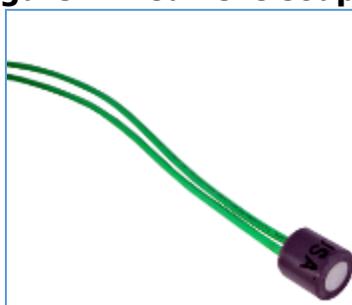


Source: GTI

The pipeline current density is measured through a steel coupon wired to the pipe (Figure 24). This device, obtained from Far West Corrosion, measures the current density through a one square centimeter surface area relative to the local soil. This provides insight into the state of the pipeline coating and the risk that corrosion is occurring. The coupon, made of steel like the pipeline, is a proxy for a coating flaw of the same area and provides a measure of the effectiveness of the cathodic protection. The soil moisture and conductivity values captured with the CS655 are also considered in the evaluation of this data.

Software is used to separate the AC and DC components of the pipeline current density. DC current is intentionally applied to pipelines to prevent corrosion. AC currents may be induced by the proximity of power lines or by ground faults in power systems. Excessive levels of AC current can cause corrosion and so must be monitored to determine if mitigation is necessary. The presence of electrified rail transit systems can also cause stray currents on pipelines that can compromise cathodic protection.

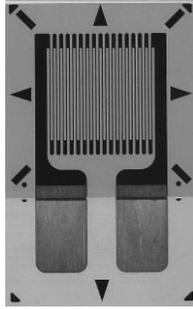
Figure 24: Current Coupon



Source: GTI

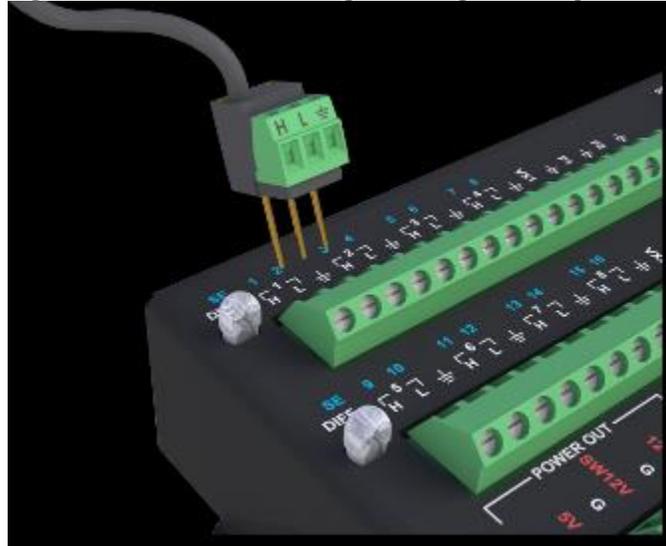
The pipe stress sensor is a strain gauge, type CEA-06-125UW-350/P2 from Vishay Micro-Measurements (Figure 25). This sensor monitors the longitudinal stress on the pipeline. The pipe stress can be affected by factors such as frost heave, undermining, or soil washout due to flooding. Stress can travel for long distances in the pipeline, allowing observation of remote effects. This effect was considered when selecting sensors so as to achieve the greatest spacing between locations. A bridge completion block, Campbell Scientific type 4WFBS350, must be used to interface the strain gauge with the CR800 data logger (Figure 26).

Figure 25: Strain Gauge Sensor



Source: Vishay MicroMeasurements

Figure 26: Strain Gauge Bridge Completion



Source: Campbell Scientific

The vibration sensor was provided by Acellent Technologies and can detect impacts at some distance along the pipe (Figure 27). This is accomplished by attaching piezoelectric vibration sensors directly to the pipe. The vibration data is then processed by a custom data acquisition system (Figure 28).

Figure 27: Piezoelectric Vibration Sensor



Source: Acellent Technologies

Figure 28: Acellent Vibration Data Acquisition System



Source: Acellent Technologies

Communication of sensor readings used the MODBUS RTU standard. The Acellent vibration monitor was configured as a MODBUS slave. It passed information to the Campbell datalogger (described in the next section) for storage. The Campbell then sent its own data and the Acellent data to the Canary RPMA wireless link in the MODBUS format.

Datalogger

Sensors readings are aggregated into a single datalogger (Figure 29). Based on the following criteria, the CR800 datalogger from Campbell Scientific was used.

- Field-hardened device that can work in harsh environments.
- Appropriate number of channels for the sensors chosen.
- Capability to directly read strain gauges with no external amplifier.
- Compatible with off the shelf soil temperature and soil moisture sensors.
- Multiple serial ports supporting MODBUS and other protocols.
- On board processing and scaling of sensor data.
- On board storage of data to provide a backup for the radio system.
- Ability to transfer data to the radio system for transmission.

Figure 29: Campbell CR800 Datalogger



Source: Campbell Scientific

Mobile Hardware

The mobile hardware is intended to provide real-time alerts of ROW activity from excavation equipment in the field based on GPS data. Excavators and vehicles are equipped with a single mobile monitoring prototype device which packages GPS, motion sensors, and other sensors to monitor their activities.

The GPS component of the mobile monitor provided the position of excavators relative to the pipeline ROW. The mobile monitor communicated with a data aggregating server through a cellular modem. Sensors for acceleration, compass heading, and rotation provided indication of when the excavator is digging. Auxiliary sensors, such as temperature, humidity, and barometer indicated if the operator of the excavator is working under conditions that may affect their safety. Data from multiple mobile monitors were sent to a dashboard where they can be viewed and correlated by utility staff.

The initial mobile sensor prototype used off-the-shelf technology (Figure 30). A single module was identified that included both the GPS function and cellular connectivity, provided by the Multitech Corporation. This was combined with external sensor modules. The completed prototype included the following sensors:

- GPS/GLONASS - global positioning system receiver, potentially combined solution with the GLONASS positioning system. The receiver requires active antennas to operate correctly.
- 3D accelerometer and gyroscope type LSM6DS0 $\pm 2/\pm 4/\pm 8$ g and $\pm 245/\pm 500/\pm 2000$.
- 3D magnetometer type LIS3MDL $\pm 4/\pm 8/\pm 12/16$ gauss acts as a compass.
- Pressure sensor (LPS25HB*: MEMS 260-1260 millibar absolute digital output barometer).
- Capacitive digital relative humidity and temperature (HTS221).

Figure 30: Mobile Prototype Sub-Assemblies



Source: GTI

During the project, the utilities providing tests sites gave guidance for their preferred embodiment of the EEN device. The goal was to have a demonstrable prototype that was closer to a commercial product. The packaged mobile prototype was tested using a rented backhoe on the GTI campus (Figure 31). While this prototype was found work, some additional features were requested by partner utilities, as described in the next section.

Figure 31: Mobile Prototype Packaged for Testing



Source: GTI

Utility Guidance for Mobile Device Format

Several items of utility guidance and feedback were captured during testing of various EEN systems both in and outside of the work sponsored by the California Energy Commission. Key guidance includes:

- Form factor needed to be smaller and more rugged (not a mobile phone).
- Power consumption needed to be low, so as not to drain vehicle batteries.
- Needed a standardized method to tie into the vehicle wiring harness for power.
- GPS antenna needed to be positioned properly to acquire the maximum number of satellites, possibly on the roof of the vehicle, separate from the main EEN device.

Five prototypes based on the cellular/GPS technology described above were tested and found to be serviceable. While these mobile devices could have been used in field testing, more advanced versions of the mobile sensors became available.

Under a separate Energy Commission Agreement, PIR-05-015, specific to a large-scale demonstration of the GPS EEN technology was ongoing during this time. The financial resources available to that project were much greater and so it was able to take the concepts past prototype and into near commercial readiness (Figure 32). This version of the GPS EEN was the one that ultimately was used in the field deployment and testing.

Figure 32: GPS EEN Near Commercial Version



Source: GTI

CHAPTER 6:

Pre-Deployment Testing

Prior to field installation, preliminary testing of the various components of the pipeline ROW monitoring system was completed. First the hardware and software components of the system for functional acceptance. Then all the components were tested as a working breadboard to demonstrate end-to-end functionality. An additional testing task, outside the original proposal, developed during the planning of the deployment with the utilities. The unanticipated testing was of additional installation methods for sensors in direct contact with the pipe metal. This development occurred when one of the participating utilities determined that the originally proposed attachment method was not in line with their established practices. As such, this chapter covers three categories of testing:

- Methods of attaching sensors that do not impair pipeline integrity
- Testing sensor functionality to ensure they meet manufacturer specifications
- Testing datalogging equipment to verify functionality and compatibility with the selected sensors

Sensor Installation Methods

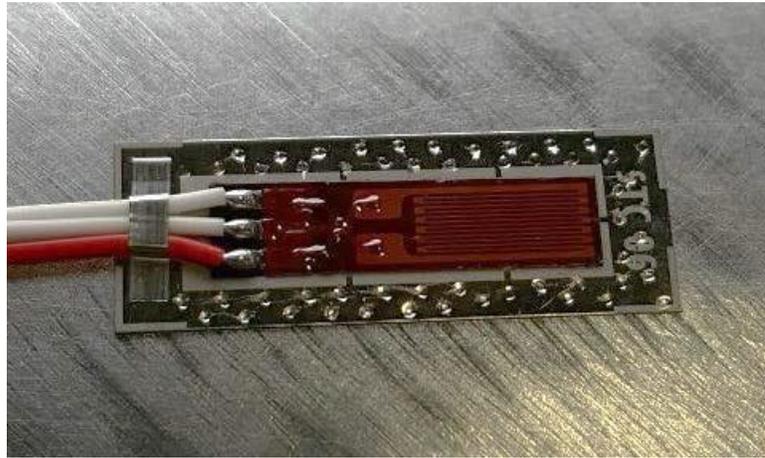
The method used to attach a sensor directly to the pipeline must not in any way degrade the performance of the pipe or its coating. The testing and demonstration required to assure this were much more extensive than anticipated at the time the original proposal. Two methods for sensor-to-pipe attachment were investigated: resistance welding and adhesive bonding.

Weldable Sensors

The original method planned for the installation of sensors on the pipe metal was electrical resistance, or “tack” welding. This method had been used to good advantage by GTI investigators in the past. Strain gauges or other sensors are pre-wired and adhesive bonded to a small metal shim under controlled conditions (Figure 33). The pre-assembled sensor is then attached to the pipe with a series of small resistance welds around the perimeter of the sensor. This technique can provide reliable bonding of sensors to metal surfaces under field conditions. The surface needs to be cleaned by grinding and polishing, then degreased. The resistance welding of the sensor is performed immediately after this cleaning. A mastic or other protective coating is put over the sensor which is then ready for use. Unlike direct adhesive bonding to the pipe, there is no curing time required in the field.

The welding is accomplished with a hand tool that is battery powered to facilitate field work (Figure 34). A tip of the size of a ball point is pressed against the shim and a pulse of current is injected that melts a small portion of the shim and the pipe metal in order to bond them together. A series of welds is needed to “tack” the sensor to the surface.

Figure 33: Weldable Strain Gauge Test Sample



Source: GTI

Figure 34: Tack Welding of Sensor

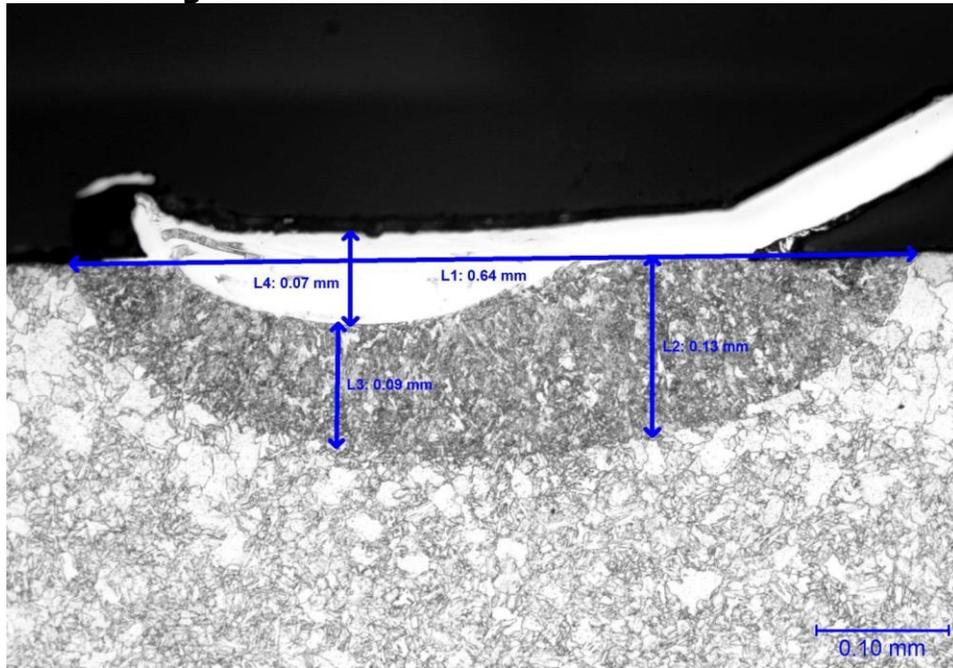


Source: GTI

Test samples were prepared for both utilities providing field sites. One utility subjected the sample to salt spray testing after the sensor area was covered with mastic; this test was passed. The second utility performed metallurgical tests on the samples. These are standard pipeline tests performed by utilities.

The weldable sensor technique was found unacceptable. The resistance welding process caused significant hardening of the metal within the weld nugget (Figure 35). The current pulse required to perform the weld produces a high heating rate within the metal that causes the hardening. The Shore hardness within the welds was found to be roughly 450; this is double the hardness of the base metal. The concern is that these hardened areas could be initiators for stress corrosion. Off-the-shelf resistance welding equipment has a narrow adjustment range for current parameters. While it may be possible to modify welding equipment to address this issue, that is outside of this scope of work.

Figure 35: Resistance Weld Cross Section



Source: PG&E

Adhesive Bonded Sensors

With the rejection of the weldable sensor technique adhesive bonding was tested. Adhesive bonding sensors to a metal surface is a well-established method of installing strain gauges. It can be successful if the bond is established within proper conditions. The conditions, taken from the Vishay Micro Measurements product literature, that must be met are stringent, which is what motivated the initial proposal of weldable sensors. As noted earlier, the weldable sensors are provided with the raw sensors already adhesive bonded to a metal shim. This manufacturing step is performed indoors, under controlled conditions. This would have eliminated the need to maintain the above list of conditions in the field.

However, results of the adhesive bonding method testing were deemed acceptable to both utilities. Test applications of adhesive bonded sensors were performed under outdoor test facility conditions at both utilities, which allowed staff to become familiar with the process (Figure 36).

Figure 36: Adhesive Bonded Sensors



Source: GTI

Site and Operator Qualifications

The adhesive attachment method dictated that GTI and the utilities identify sites where the appropriate conditions could be maintained. The sites had to provide open trenches that allowed access to the pipe and removal of the coating. The trench needs to be open for a time sufficient to allow surface preparation, sensor application, and for the adhesive to cure. Provisions must be made to maintain the temperature and moisture levels during installation. Even with supplemental heat and pumps, this can be difficult during cold or rainy conditions. This narrowed the pool of available job sites to those scheduled during times when extreme weather is unlikely.

On due consideration, the utilities decided that they would only allow this operation on out-of-service pipelines. This means that the pipe is not transporting gas at the time the sensors are installed. This further narrowed the acceptable job sites to those involving new pipe installations or the line being taken out of service for maintenance. While the adhesive attachment method does not cause any harm to the pipe, the additional approvals needed to perform this operation on a live pipe would have required more time than was available in the schedule. Utilities can pursue qualifying the operation on live pipe for future deployments.

Another issue is operator qualification. The personnel performing the sensor attachment must be cleared by the utility to perform this type of work on their infrastructure. In one case, the utility did have internal staff that was familiar with applying strain gauges with adhesives. These personnel were designated as qualified to perform the application for their sites. In the other case, the utility made allowance for GTI staff to perform the application.

Sensor Functional Testing

Functional tests of the various sensors were performed under laboratory conditions. This testing had two aspects: testing of the sensor and testing of the datalogger and associated software interfaced to the sensor.

Vibration Sensors

The piezoelectric vibration sensors (left side of Figure 36) and the seismic geophone sensors were connected to the Acellent vibration analyzer device. Pre-deployment testing of the Acellent hardware has been carried out in their laboratory in Sunnyvale, California. This testing will be the subject of a separate report issued by Acellent Technologies as part of PIR-14-015.

Strain Sensors

Two different methods were used to test the strain sensors in the laboratory. First a small load cell was connected to the Campbell CR800 datalogger. This load cell is a strain gauge bridge that can measure up to 1,000 grams. The load cell could easily be actuated by hand or by placing a fixed weight on it. This produced change in the reading, allowing the hardware to be debugged. Some additional testing was carried out with a strain gauges on a steel plate.

Strain measurements were recorded on the actual test site during a pipeline hydro-test. A hydro-test consists of filling the pipeline with water that is pressurized to a known level as a means of testing the pipe and all welds. This test provided calibration data for the strain gauges. The hydro-testing also exposed the sensors to temperature and moisture conditions that were not available in the lab. The various sensors that could be tested with no external protection in the lab required an elaborate coating system to protect them from the environment.

Pipe Current Sensing

Pipe current density is standard measure of how well the pipeline is cathodically protected from corrosion. To accomplish this, a wire is metalically connected to the pipeline. This wire is then connected to a small steel coupon that is buried in the soil. This coupon is the same material as the pipeline and typically has an area of one square centimeter exposed to the soil. The coupon area is a proxy for a break in the pipeline coating. Measuring the current passing through the wire from the pipe to the soil through the coupon provides a measure of the current available to protect the pipe in the event of a real break in the coating.

Campbell CR800 software was developed to measure the current density on the coupon. This consists of combined DC and AC components. The software sampled the current value and processes it into DC and AC components. The DC component is derived by averaging multiple samples. The sign of the DC component provides an indicator of proper cathodic protection; in a properly operating system current flows from the soil to the pipe. The magnitude of the DC component indicates the amount of protection required relative to local conditions. The AC component is derived from the standard deviation of multiple samples. In the absence of any induced or conductive AC current from nearby power lines, the standard deviation of the current signal will be low.

The current input to the CR800 was laboratory simulated using a programmable waveform generator (Figure 37). This device can generate waveforms with sinusoidal characteristics and DC offsets. Sinusoids at 60 Hz and its harmonics were used along with offsets that would be typical under field conditions. This allowed appropriate software to be developed for the CR800.

Figure 37: Calibration Signal Generator

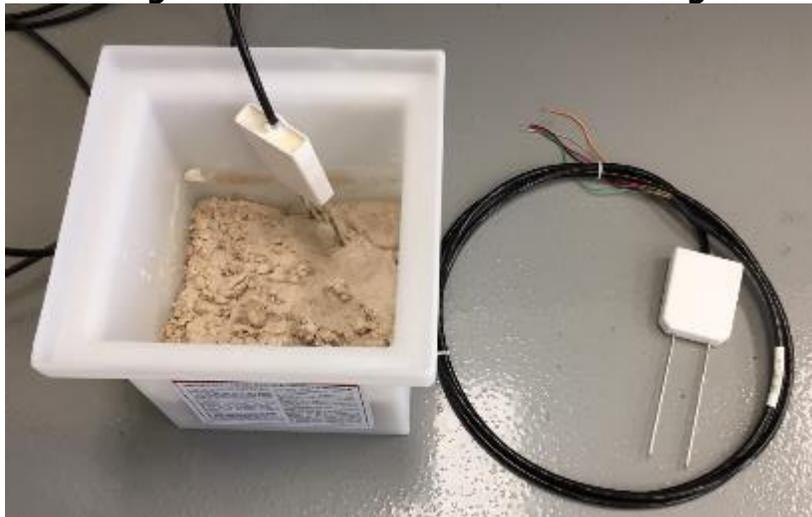


Source: GTI

Test of Sensors for Pipe Moisture, Temperature, and Conductivity

The Campbell Scientific CS655 probe was used to measure three different soil parameters: temperature, conductivity, and water content (Figure 38). The sensing mechanism requires two metal probes in contact with the soil. The sensor is buried, and the cable run to the datalogger location. The laboratory testing was facilitated with a container of soil that water can be added or allowed to dry out.

Figure 38: CS655 Soil Sensor Testing



Source: GTI

The soil parameters measured are the temperature, soil moisture, and soil conductivity. The specifications for the various parameters are given in Table 1.

Table 1: Soil Sensor Specifications

Parameter	Range	Accuracy	Precision
Water Content	0 to 100% Volume	+/- 3%	0.05%
Temperature	-50 to +70 C	+/-0.1 C	0.02 C
Conductivity	0 to 8 dS/m	+/- 5% of reading	0.5%

Source: GTI

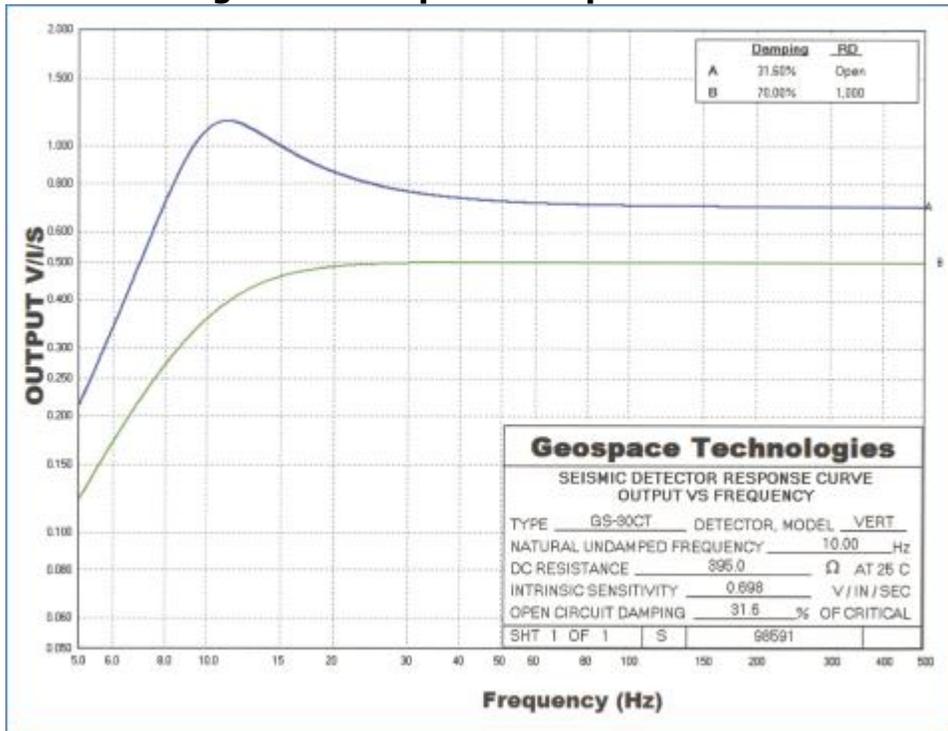
The CS655 devices are shipped pre-calibrated by Campbell Scientific. The laboratory testing of these was intended to verify the correct functioning of the Campbell software rather than an additional calibration of the sensor. Note that the conductivity is measured directly by the sensor and the water content is then calculated from the conductivity. All observed test data agreed with the specifications.

The soil conditions will be used in conjunction with other parameters as an indicator of conditions on the ROW. The soil conductivity is driven by moisture and will interact with the pipeline current measurement. A very low current through the pipe sensing coupon (described in the previous section) in conjunction with low soil conductivity is a reasonable finding. Low current in a more conductive soil is indicative of good cathodic protection. Other correlations, such as high moisture content with high strain might be indicative of a washout in progress. For soil temperature, frost penetrating the soil deeply can produce strain on the pipe. At very extreme temperatures, frozen soil can physically move the pipe, a condition known as "frost heave".

Soil Seismic Sensor

A geophone is placed in the soil alongside the pipe to determine if there is a seismic event or strong vibration source in the area. It does this by measuring the movement of the soil that it is embedded in. As with the soil sensor, the geophone was calibrated by placing it in a container filled with soil. The container in turn, was placed on a small Bruel and Kjaer shaker table. This allowed known frequency signals to be injected into the geophone. This testing verified that the geophone was working properly but also indicated that the CR800 did not have sufficient bandwidth to work with this sensor. The calibration curve for the geophone shows its frequency response (Figure 39).

Figure 39: Geophone Response Curve



Source: GTI

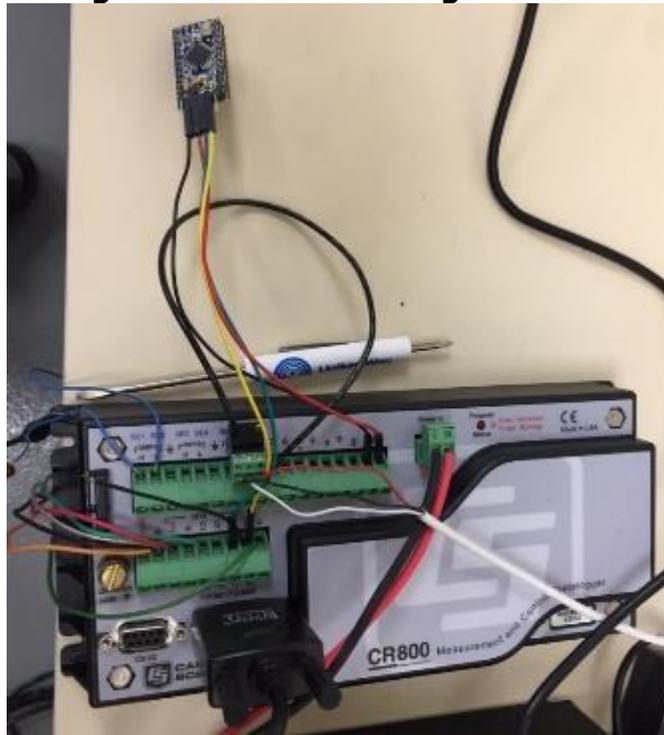
Based on its frequency response describe above, it was decided that the geophone would be connected to the Acellent vibration analyzer equipment. The Acellent equipment captures the seismic data and provides and provides information on the frequency and amplitude of the soil motion.

Datalogger Testing

Along with the testing of the various sensors described, testing of the data acquisition and logging equipment was also carried out.

The Campbell Scientific CR800 (Figure 40) is the backbone of the data acquisition system. Except for the vibration sensors and geophone, all sensors and radio equipment are connected to the CR800. The testing of the various sensors in the lab allowed extensive testing of the CR800 capabilities. The CR BASIC routines to capture the data were developed during this testing. An auxiliary board (upper left) was used to simulate the MODBUS output from the Acellent device so that this connectivity could be exercised and programmed. No completely functional Acellent devices were available during the pre-installation testing period; these only became available after the field deployment was in progress.

Figure 40: Bench Testing of CR800



Source: GTI

The data stored internal to the datalogger can be recovered as a CSV file. There are four megabytes of internal memory that is shared between the program and data storage. The CSV file can be opened by other tools, such as Excel, to allow analysis. An example of such data is given in Appendix A. Up to four million readings can be archived internal to the CR800. This allows a backup copy of the data in the event the radio system fails. The data rate and number of sensors affects how quickly the internal storage is used. The oldest data is overwritten by the newest in a circular buffer when capacity is exceeded. The current data usage will allow slightly over four days of storage before overwriting occurs.

CHAPTER 7:

Deployment of Monitor Hardware

This chapter describes the use of equipment on the test site as well as an installation procedure on new pipe prior to commissioning. Procedures for installation on in-service or older pipes may be developed at a future time.

Sensor Deployment

The following serves to document the installation procedure that was developed by the utility hosting the site and the sensor providers. The procedure described assumes that the pipe is not in service at the time of installation. The pipe may be new and not yet commissioned or taken out of service for maintenance.

Prepare Excavation

A properly shored trench that provides 360-degree access to the pipe is required. The trench should be at least 4' wide and 8' long as seen in Figure 41. Safe access to the excavation must be provided. Conduits to bring sensor cables to the surface can be placed in advance. The pipe surface must be kept dry during the installation so as not to contaminate the adhesive. The excavation must be free of water; pumps may be required. The temperature affects the curing time for the epoxy used to attach sensors. At this site, temperatures exceeded 100°F with very low humidity. While unpleasant for personnel, hot and dry conditions are excellent for adhesive bonding. It was not necessary to bring in heaters or water pumps. The heat did accelerate the curing time of the epoxy adhesive.

Figure 41: Excavation for Sensor Installation



Source: GTI

Pipe Surface Preparation

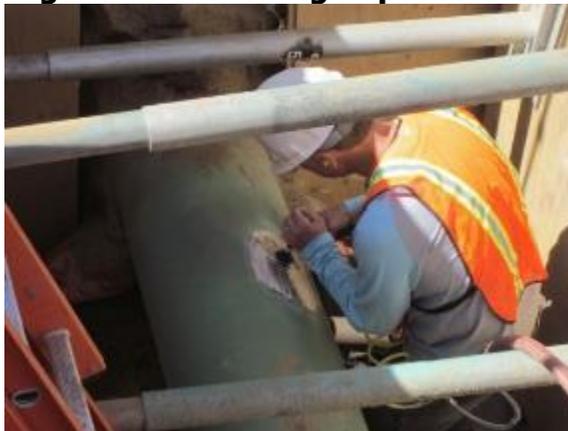
Utility personnel removed the outer coating over a roughly 6" by 6" area of pipe surface. The crew may perform additional coarse abrasion if rust or scale is present. The sensor placement area must be free of large pits, gouges, or seams.

When working within an excavation it always necessary to follow safety practices. There must be correct shoring to support the sides of the trench. A ladder or other easily accessible means of egress must be provided. Hard hats, safety glasses, and other appropriate personal protective equipment must be worn.

The following procedure (in detail) can be found in the Vishay Micro Measurements literature, which provides the surface preparation methods for the installation of strain gauges. A synopsis is given here.

- Degrease pipe surface to prevent contaminants being driven into surface.
- An air or electric grinder with successively finer abrasive pads is used to smooth the pipe surface (Figure 42).
- Degrease the pipe surface between changes of abrasive pad.
- Hand polish the pipe surface with 320 grit then 400 grit paper to further improve finish.
- Use a straight edge and burnishing tool or ballpoint to mark layout lines on the pipe surface. For this project, the layout lines are parallel to the longitudinal direction, or flow direction of the pipe.
- Wet clean the surface with M-Prep Conditioner being careful not to remove the layout lines.
- Clean the surface again with gauze sponges and M-Prep Neutralizer.
- Wipe from the interior of the cleaned area outward in one stroke. Do not re-use gauze as it may contaminate the surface.

Figure 42: Polishing Exposed Metal



Source: GTI

Sensor Application

Sensor application was done immediately after completing the surface prep and cleaning.

- For vibration sensors, clean the back surface with degreaser.
- For strain gauges, leave in plastic covers until just before application. When performing this work under field conditions, it is good practice to install an extra strain gauge as a backup. Most installation time is taken up by the surface preparation; the additional labor to install an extra gauge is minimal. This helps ensure that a good gauge

installation is available. Pre-position the sensors and tape down leads outside of cleaned area.

- Use the layout lines to orient strain gauges with the sensitive axis in the longitudinal direction.
- Mix the appropriate amount of the AE-10 epoxy for the sensors. Generally, one 10-gram package is enough for four sensors. The pot life of the epoxy is roughly 20 minutes after mixing but can be reduced if the ambient temperature is high. If the installation time is long or the temperature is high so that the AE-10 epoxy becomes too viscous to work with, an additional package can be mixed and used.
- Use a stirring rod to apply epoxy to pipe surface. Position sensors with tweezers and/or dental pick.
- Cover sensor with Teflon tape, then apply magnet or other clamping mechanism over the tape (Figure 43).
- Wait for epoxy to cure based on ambient temperature: roughly four hours at 74 degrees F. Supplemental heat may be needed during cold weather.
- Care must be taken to exclude water from the sensor area during the cure time.

Figure 43: Sensors During Epoxy Cure



Source: GTI

- Remove magnets and Teflon tape from sensors.
- Test strain gauges with an appropriate instrument (Figure 44) or with an ohm meter. If the gauge is properly bonded, pressing with a finger or pencil eraser will not cause a change in strain level.
- Test vibration sensors with Acellent instrument or oscilloscope.
- If a sensor installation is found to be questionable it should be removed and/or replaced. If a "spare" sensor was installed, the best practice is to cut the cable from the suspect sensor to prevent later confusion.

Figure 44: Testing Strain Sensors

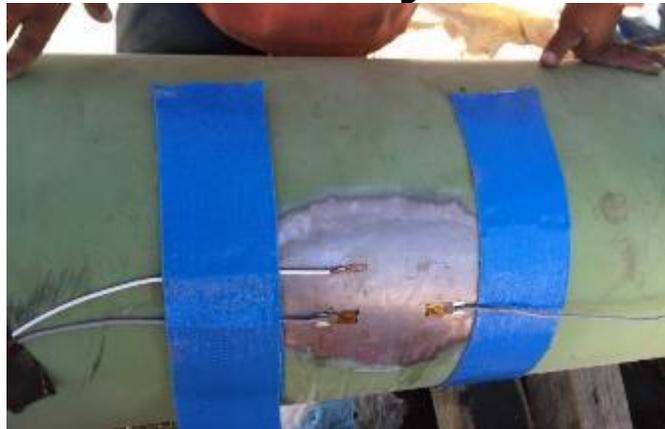


Source: GTI

Protective Covering

- Prior to applying the covering, wipe down area adjacent to sensors with acetone for full 360 degrees.
- The covering used for this installation is a two-layer tape system called Viscotaq. Bracket the immediate sensor area with two strips of Viscotaq.
- Press cables into first layer of Viscotaq and sandwich with additional strip (Figure 45). Cover over sensor area with additional strips perpendicular to the border strips to form a patch.

Figure 45: Protective Covering over Sensor Area



Source: GTI

- Over the sensor protection patch, perform a spiral wrap of the pipe with Viscotaq as per manufacturer instructions. Start wrap at least 6" before sensor area; continue wrap to 6" beyond sensor area.
- Counter wrap the pipe with a layer of PVC tape over the top of the Viscotaq (Figure 46).
- Test all sensors again prior to backfill.
- The first (blue) layer is pliable material that bonds well to itself and the pipe metal to exclude water. It also bonds with the (black) PVC layer that provides bump and abrasion protection.

Figure 46: PVC Tape Wrap Application

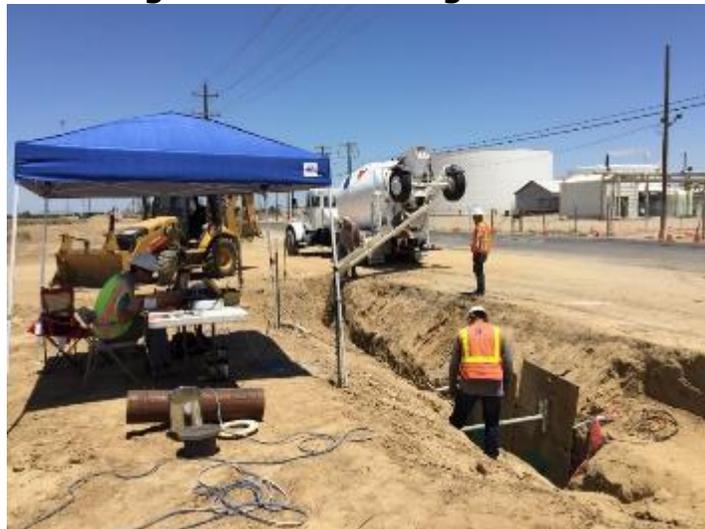


Source: GTI

Backfill and Soil Sensor Installation

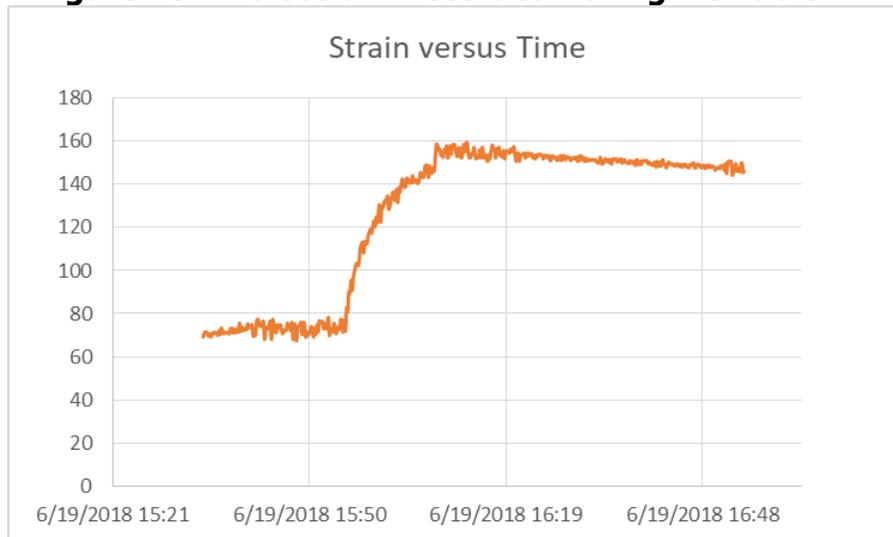
- Position excess sensor cable near the edge of excavation and on the bank.
- If the data logging equipment is available, it can be hooked up to record pipe strain during the back-fill process (Figure 47; Figure 48). The change in pipe strain level during fill indicated that the gauges are working correctly. The slight decrease in strain after backfilling is caused by the water in the slurry evaporating or being absorbed by the surrounding soil.
- Begin filling trench with zero sack or other flowable fill, taking care not to strike the cables. A flowable fill, or slurry, was used for the initial backfill to protect the pipe, sensors, and cables from being damaged by stones or other inclusions that might be present in native soil backfill.

Figure 47: Monitoring Back Fill



Source: GTI

Figure 48: Microstrain Recorded During Flowable Fill



Source: GTI

- Flow the fill material from alternate sides of the sensor area to achieve a fill level to roughly 18" above the top of the pipe (Figure 49).
- When the fill level has been achieved, allow the fill to set for 1-2 hours until the surface becomes firm enough to walk on.

Figure 49: Excavation Partially Filled over Sensor Area



Source: GTI

- After the fill has set sufficiently, make a roughly 12" by 18" excavation by hand, about 18" to the side of the pipeline. Insert the soil sensors into this excavation with the geophone in the center.
- Place the soil moisture and current coupon sensors at opposite ends of the hand excavation.
- Taking care to place the soil sensor cables on the bank, fill the 12" by 18" excavation by hand (Figure 50).
- After all sensors are installed under flowable fill, repeat tests using datalogging equipment and/or testers to verify that all sensors are working.

Figure 50: Sensors Installed



Source: GTI

- The sensor cables are then run through conduit from the top of the flowable fill to the surface of the ground. This is in preparation for the installation of the instrument cabinets.
- When the cables are within conduit, standard soil backfill can be used for the remainder of the excavation without fear of damaging cables or sensors.

Hydro-Test of Pipeline

This section describes an additional testing opportunity to capture calibration data for the strain sensors that became available during this project. As part of the normal practice of installing a new utility pipeline, this pipeline was hydro-tested in early July 2018, shortly after the sensors were installed. In a “hydro” test the pipeline is filled with water that is then pressurized to test the integrity of the new pipe. The use of water is used as it is not flammable and it will depressurize rapidly if a break occurs.

The permanent instrument enclosures were not complete at the time of the hydro-test. The instrumentation was temporarily used for a three-day period to capture this data (Figure 51). This provided test data for some of the major systems. There was no cathodic protection in place during the hydro-test, preventing testing of the current coupon. The instrumentation was run from a combination of batteries and/or generators. The RPMA radios were not available making it necessary to recover the test data by directly connecting to a laptop (Figure 52).

Figure 51: Instrumentation Running on Battery Power



Source: GTI

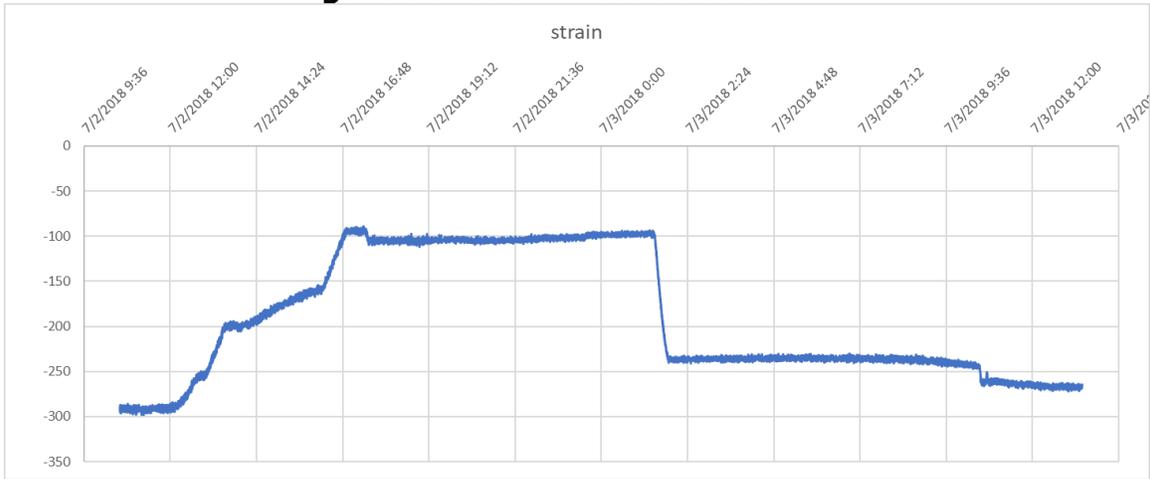
Figure 52: Recovering Hydrotest Data



Source: GTI

The following plots show longitudinal pipe strain data that was captured over the course of the hydro-test. It should be noted that the starting or “zero point” of a strain gauge is arbitrary. One can establish an artificial zero by adding an offset to all the readings. Given that the installations were not completely backfilled at this time, we chose not to. The pressure profile ramps up to a spike value for roughly 15 minutes (Figure 53). The pressure is then held at 80% of maximum allowable operating pressure for eight hours. After that time the pressure was released, and removal of the water started. The tail end of the graph is still somewhat elevated as not all the water had been purged yet. The first hydro-test strain plot shows a station that was run purely on battery power for the entire duration of the test (Figure 53). The strain very clearly follows the hydro-test pressure profile.

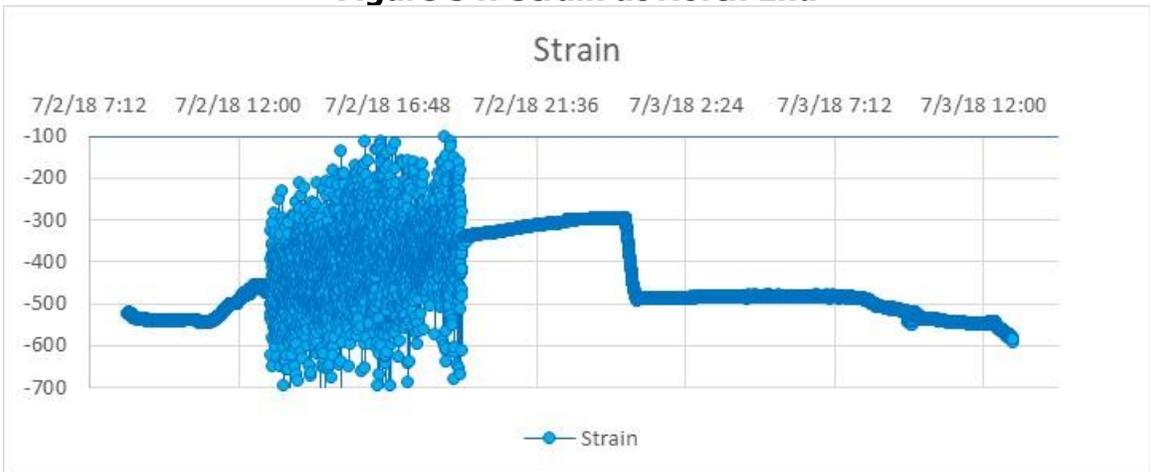
Figure 53: Strain Data at South End



Source: GTI

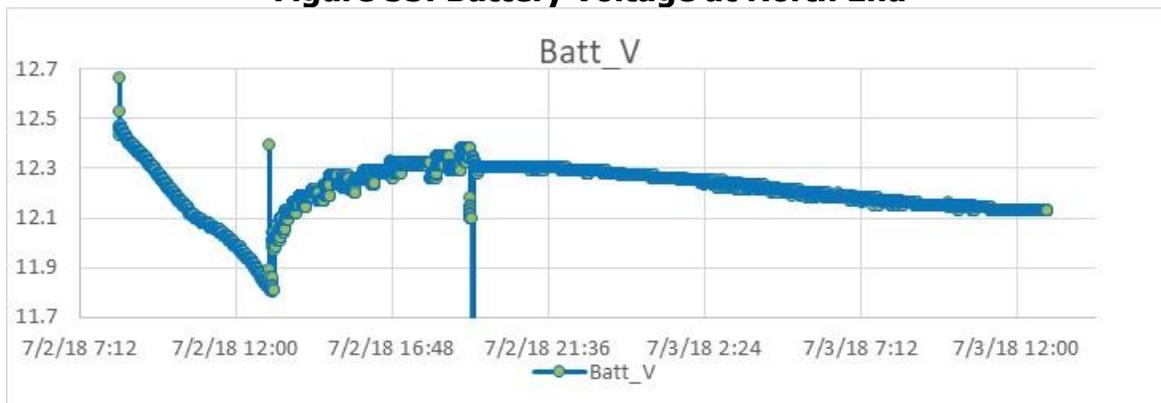
The strain data recorded at a location 4000' north on the pipe showed a noise artifact for part of the test (Figure 54). This noise is attributable to the use of a generator to recharge the instrumentation batteries. The battery voltage plot for the same location clearly shows when the generator was being run to charge the batteries (Figure 55). The noise is caused by inadequate grounding of the generator. Even a small fraction of the AC current going to earth ground through instrument cables causes significant noise. Truck mounted temporary generators do not provide intrinsic earth grounding. In some locations, it is possible to drive a temporary ground into the earth and connect the generator to this. The earth is so dry at this location that a hand driven ground rod was ineffective. The permanent enclosures, which were not complete at the time of the hydro-test, have large surface-area grounding structures that are buried at pipeline depth (roughly 6').

Figure 54: Strain at North End



Source: GTI

Figure 55: Battery Voltage at North End



Source: GTI

Initial Enclosure Installations

After the hydro-test was complete, the instrumentation was removed to a safe storage area in the construction yard until the permanent enclosures could be completed. The sensor cables were pulled through conduits and brought above ground. Footings were poured at two locations to support the pole for the instrumentation cabinet during July (Figure 56). The remainder of the soil backfill was put in place on top of the slurry fill covering the pipe.

Figure 56: Footing and Conduit in Place



Source: GTI

The poles were put in place and the permanent enclosures with their solar power system installed (Figure 57). The CR800 dataloggers were installed and wired and cables from the previously installed sensors were brought to the surface in conduits. The Acellent vibration processors and RPMA radios would be installed later. Space was left at the top of the 15' pole for the radio enclosure. This installation is typical for two of the three locations on this site.

Figure 57: Solar Powered Enclosure in Place



Source: GTI

The third location on the test site to house instrumentation was inside the fence of a permanent station being constructed by a partner utility. The array of sensors is the same as the other locations, but the instrumentation resided in an equipment shed that will be supplied with AC mains power (Figure 58). A 15' mast was provided between the two sheds for the RPMA radio equipment antennas. The equipment in these sheds was temporarily powered by a generator, pending the completion of the AC power tie-in.

Figure 58: Equipment Sheds at Location 3 Under Construction



Source: GTI

Initial Vibration Testing

A series of tests were carried out to verify the response of the system to vibrations and impacts. This testing involved locations one and two only; the equipment shed at location three was under construction at the time. For this series of tests, the Acellent signal processing equipment was installed in the enclosure and connected to the sensors. The utility provided a soil compactor and an excavator to support this testing (Figure 59).

Compactor testing put repeatable vibrations into the ground at known locations between station one and station two. This would provide data on the sensitivity of the vibration sensors mounted on the pipe and on the attenuation of the soil-pipe system. The compactor testing began 50' south of location one and proceeded continuously over the pipeline to a point 50' to the north (Figure 60). The testing continued proceeding north toward location two with the compactor being moved to discrete points rather than run continuously (Figure 61). These points were 100', 200', 400', 600', 800', and 1,000' north of location one. The compactor was run for roughly two minutes at each point. The last point in this series was roughly 43' south of location two. To complete the series the compactor was run continuously from this point to on 50' to the north of location two.

Figure 59: Equipment Enclosure Interior View



Source: GTI

Figure 60: Compactor Testing



Source: GTI

Figure 61: Test Site Overview



Source: GTI

The excavator testing made use of a piece of equipment that is typical of what is used for digging and trenching operations (Figure 62). The impact signals generated by the excavator, while not repetitive like a compactor, should be larger in magnitude. This test was carried out at the same set of discrete points as the compactor but in reverse order. The excavator started at a point 50' to the north of location two and proceeded to a point 50' to the south of location one. At each point the excavator removed a small amount of soil, impacted the arm onto the ground several times, and then replaced the soil. At no time was more than 12" of soil removed or was there any hazard to the pipeline.

Figure 62: Excavator Testing



Source: GTI

At the end of this testing sequence the excavating equipment withdrew from the site and the data was recovered from the recording equipment. It was found at this time that the Acellent equipment had failed to record any vibration events and also appeared to be overheating.

Based on these results, Acellent removed the signal processors from the enclosures and put them through further testing. The equipment was found to be in working order. Acellent set up a pipe with sensors at their facility and performed several impact tests to determine the noise floor and sensitivity. The determination was that several gain and trigger threshold values had not been set appropriately for the actual field conditions. Acellent had anticipated, based on their in-house testing, the signal magnitudes generated by soil impacts would be greater and had set the trigger values accordingly.

Acellent then returned the equipment to the test site to run several diagnostic tests and measure the equipment noise floor on the actual site. These activities allowed the appropriate settings to be established. Acellent reported that they were able to record some background events during this round of testing.

CHAPTER 8:

Field Testing and Results

At this point in the project, the equipment was largely in place on the test site. Testing of all the various sensors had been carried out individually. The overall system was now ready to be tested. In this chapter we will see how multiple sensors, when considered together, provide a more complete picture of conditions on the site than any single sensor in isolation.

The hierarchy of components, starting from remote sensors and working towards the user interface, is given below. The various items will be discussed in this order.

- Mobile devices mounted on excavation/construction equipment captures and transmits status data to the hosted repository by a cellular connection. This data includes:
 - The GPS location of the equipment along with its speed and bearing.
 - Accelerometer and gyro data to infer what activity the equipment is performing.
- A vibration monitoring system captures sensor data and forwards it to the datalogger. The geophone requires faster processing than the datalogger was capable of. This was addressed by connecting the geophone to the Acellent processing equipment.
 - Two piezoelectric sensors are mounted directly on the pipe.
 - A geophone is embedded in the soil alongside the pipe.
- Local instrumentation consists of a datalogger that captures data from sensors and sends it to the wireless device through a wired connection. These sensors are:
 - A strain gauge mounted directly on the pipe surface.
 - A current sensing wire connected directly to the pipe.
 - A conductivity/moisture sensor in the adjacent soil.
 - A temperature sensor also in the soil.
- A wireless endpoint is provided for each set of sensors along the pipeline. The endpoint collects data from local instrumentation and forwards it by radio to the web hosted repository.
- The ROW data is visualized on a web-hosted, user dashboard. The data for the dashboard is stored in the web-hosted repository.

Mobile Sensor Testing

A basic assumption of this project, as discussed in Chapter 1, is that excavation equipment is a primary threat to buried infrastructure. This assumption is supported by multi-year studies performed by PHMSA, results of which are highlighted in Chapter 1. Mobile sensors with GPS technology provide the location, heading, speed, and status of excavation/construction equipment (Figure 63).

Figure 63: EEN Device Prototype



Source: GTI

A first-generation prototype of the EEN device was constructed and tested early in this project. An additional project was funded by the Energy Commission (PIR-15-015) that produced pre-commercial prototypes. These devices were more advanced than the original prototypes and were readily available at the time of field testing. The original test plan had included simultaneously testing the stationary vibration sensors and EEN sensors on excavators in same ROW (Figure 64).

Figure 64: EEN Prototype on Excavator



Source: GTI

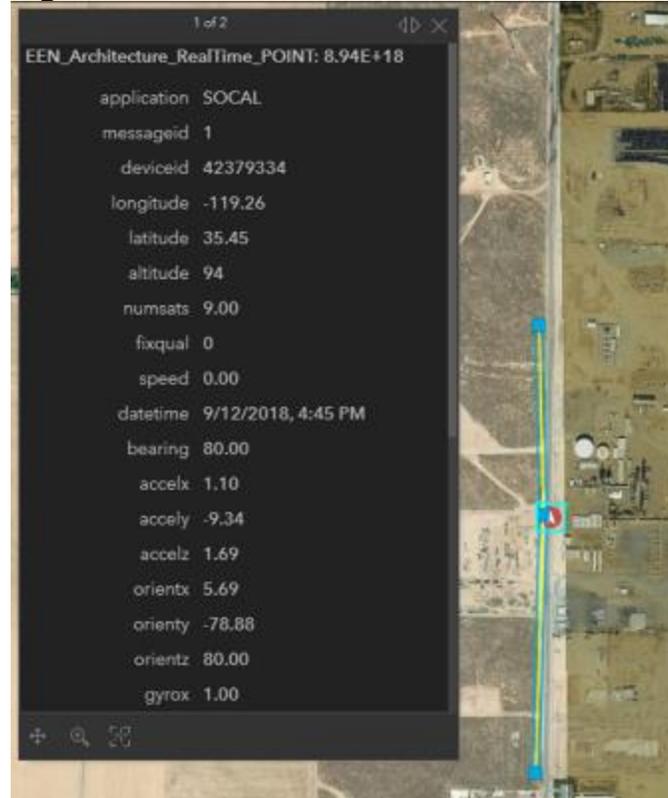
During the actual field testing access to excavation equipment was limited to less than one day. There were issues with the stationary vibration sensing equipment, discussed in the next section, such that the utility hosting the test site did not provide a second round of excavator testing. In place of the excavator testing, the EEN device was placed in several vehicles that were used on the test site. This allowed several key attributes of the EEN devices to be tested, including:

- Cellular coverage on-site was adequate to track EEN devices.
- Geo-fence around the pipeline on the test site was successfully established.

- Notifications were generated when the EEN device entered the geo-fenced area.
- Notifications were successfully displayed on the same operations dashboard as the stationary sensor data.

Figure 65 shows representative test data as presented in the user dashboard. The symbology is as follows: the EEN device is the red circle with the inscribed triangle. The pipeline is shown in yellow and its geo-fence as the two blue lines that bracket the pipeline. In this case the geo-fence area is set for 25' on either side of the pipe location. The stationary sensor locations are designated with light blue squares. Clicking on the EEN device symbol in the dashboard will produce a drop-down display with the most recent data received.

Figure 65: EEN Device Data on Dashboard



Source: GTI

Additional Vibration Testing

The vibration sensors provide early indication of activity on/near the pipeline ROW. There are two sensors directly attached to the pipe at each sensor station to measure vibrations travelling directly in the pipe material.

The vibration testing of the equipment was repeated over two days using a soil compactor as the signal source. Data from this testing was captured both as processed data in the datalogger and as raw data within the Acellent vibration processing equipment. This section will provide a detailed look at the testing at Station 1, located at the south end of the test site. With minor variations, this data is typical of all three stations.

For the second round of vibration testing a soil compactor was operated near the buried sensors at Station 1. The first test occurred on top of the sensor location. For the second test,

the compactor was moved to a location 75' from the sensors (Figure 66). The compactor was operated for two minutes continuously in both locations.

Figure 66: Vibration Test with Compactor



Source: GTI

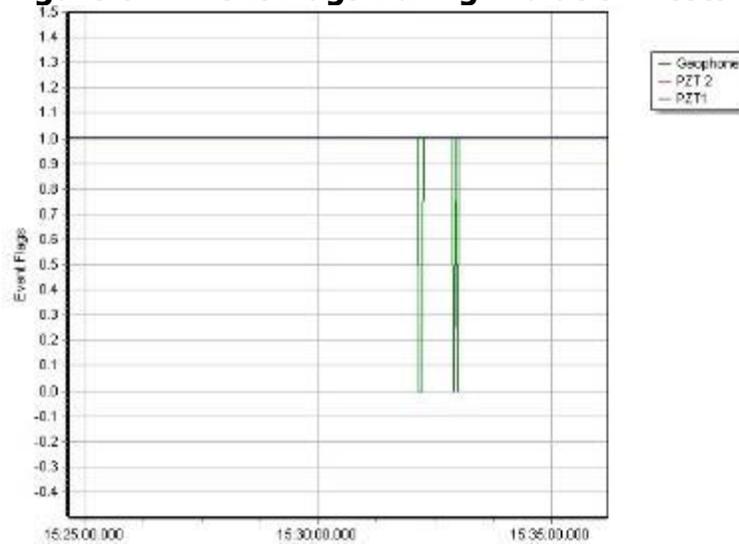
The raw data was recorded by the Acellent vibration monitor and a processed version of the data was passed to the Campbell datalogger (CR800) for storage and forwarding. The radio system was not active the day of the vibration test and so storage in the web-hosted system was not available.

The processed version of the data passed to the CR800 is based on the Fast Fourier Transform (FFT) of the raw data and statistics. For each of the three vibration channels the following five parameters are provided.

- Mean value of the raw signal
- Standard deviation of the raw signal
- Frequency of the highest peak in FFT of the raw signal: F1
- Frequency of the second highest peak in the FFT: F2
- An alarm flag that is set to one if a significant change in F1 or F2 is detected, zero otherwise.

The following graphs use the processed data passed to the CR800 datalogger during the vibration test. As noted earlier, the test was carried out at two locations. At time 15:26, the soil compactor was run in the immediate vicinity of the buried sensors for roughly three minutes. The compactor was then moved 75' north of the sensor location, but still directly above the pipe, and started at 15:31. Again, it was run for roughly three minutes. One would expect the event flags to transition from 0 to 1. This is not observed in the data; the event flags stayed in the "alarm=1" state for most of the observed time, providing no clear indication of when the compactor was operating (Figure 67). The algorithm that determines when to set the alarm appears to be ineffective.

Figure 67: Event Flags During Vibration Tests

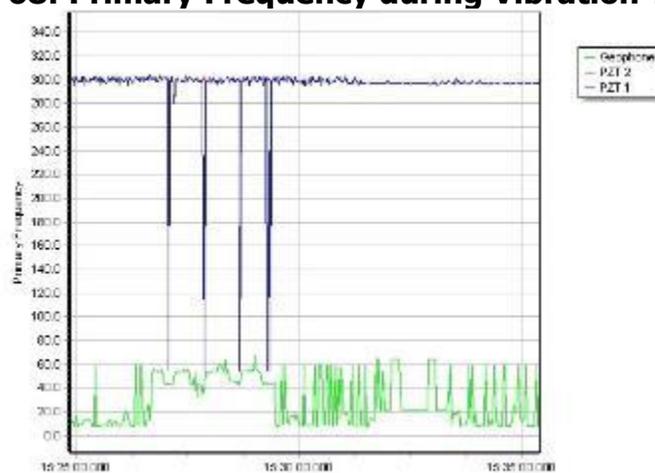


Source: GTI

The other indicator proposed by Acellent was that the dominant frequencies in the FFT would shift when the vibration sensors were exposed to a signal in the pipe. There is an observable shift in the frequencies seen during this test (Figure 68). The highest, and the second highest components the signal FFT in Hertz are provided (Figure 69). The geophone and vibration sensors (PZT1 and PZT2) both clearly show frequency shifts during the close testing interval. The response is there during the far testing interval but to a lesser degree.

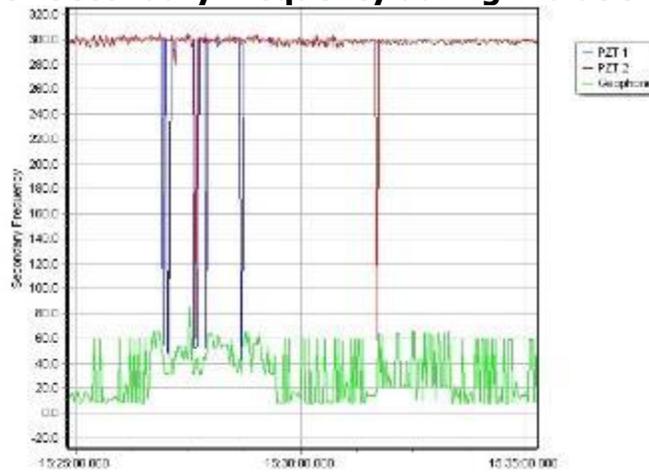
The data shows that when the soil compactor was in the immediate vicinity (time 15:26), there was observable changes in the frequency (in Hz) across all sensors. In some instances, the dominant frequencies of the piezoelectric sensors and geophone came close to coinciding. When the compactor was moved 75' north (time 15:31) along the pipe, the effect is diminished. It is more reliably observed in the geophone than the piezoelectric sensors. The frequency shift data is more reliable than the alarm flags.

Figure 68: Primary Frequency during Vibration Testing



Source: GTI

Figure 69: Secondary Frequency during Vibration Testing

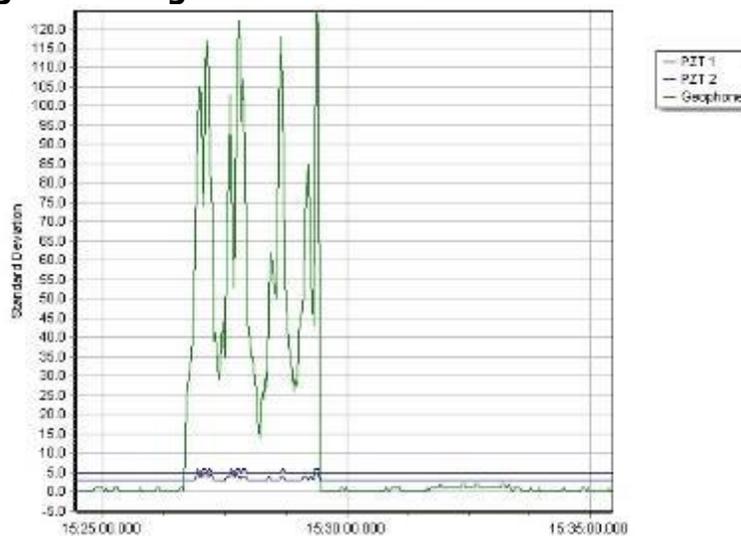


Source: GTI

A more reliable indicator of activity than the error flag or frequency shift provided by the Accellent vibration monitor is still needed. The standard deviation of the signal is an indicator of vibration signal strength (Figure 70). The signal strength provides a clearer indication of when the compactor starts and stops. The geophone buried in the soil provided a much stronger response to the compactor than the vibration sensors, PZT 1 and PZT 2. These vibration sensors are roughly 18" apart on the pipe surface.

When looking at only the response of the piezoelectric sensors, there is indication that they were able to detect the nearer of the two vibration tests (Figure 71). When looking specifically at the far test, with the compactor 75' from the sensors, the geophone still shows a small response to the excitation (Figure 72). The two piezoelectric sensors do not show any deviation from their baseline values whatsoever.

Figure 70: Signal Standard Deviations for Near Test



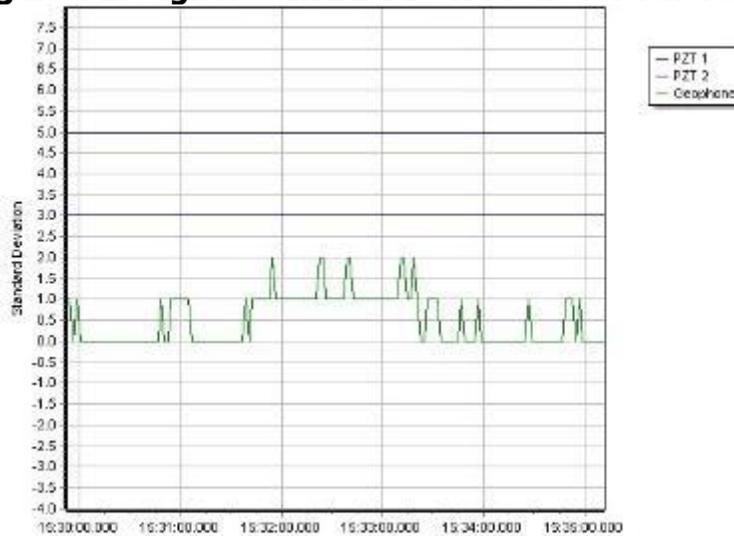
Source: GTI

Figure 71: Standard Deviation for PZT Sensors Only



Source: GTI

Figure 72: Signal Standard Deviations for Far Test



Source: GTI

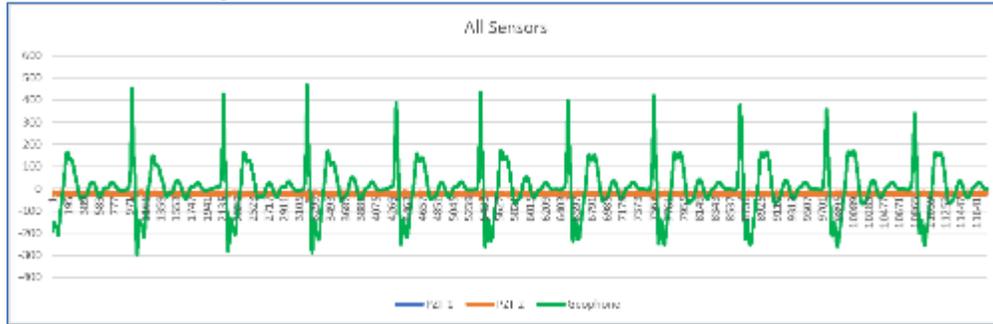
The raw vibration monitor data consists of 1-second bursts of the signal. The horizontal axis is in sample numbers; the data sets were acquired at a 12 kHz sampling rate. The vertical axis is given in analog to digital converter (ADC) counts rather than engineering units. Full scale for the ADC spans +/- 32,767 counts. These are plotted to provide the time waveform of the signals.

The soil compactor was moved across the area that contains the geophone and the vibration sensors. Figure 73 shows a point in time when the compactor was closer to the sensor location and the signals correspondingly greater. Figure 74 shows the signal for vibration sensor PZT 1 over the same time interval.

The shape of the waveform response for the two sensors clearly corresponds in this instance. However, there is an obvious disparity in sensitivity. The geophone shows a peak to peak excursion of roughly 700 counts. The PZT vibration sensor must be re-scaled for the peak to

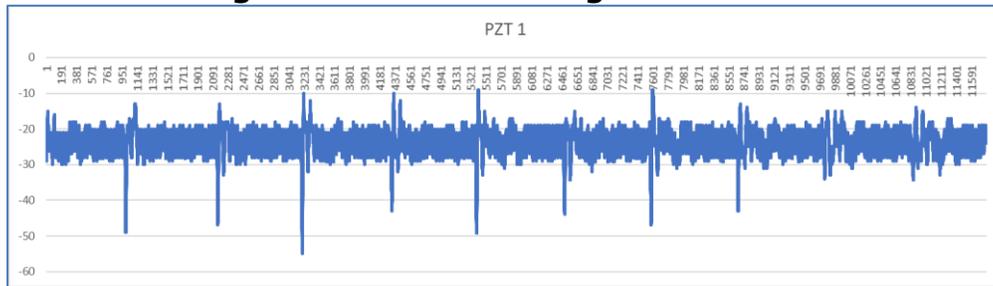
peak excursion of roughly 40 counts to be visible. Acellent was repeatedly asked if there was some means to provide additional gain to signal built-in to the Acellent vibration monitor and they maintained there is not.

Figure 73: Raw Vibration Data 15:27:00



Source: GTI

Figure 74: Raw PZT 1 Signal 15:27:00

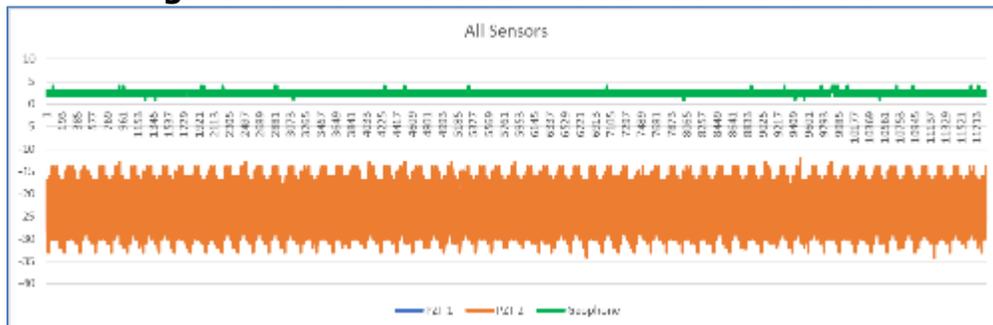


Source: GTI

Raw data was also captured during the quiet interval when the compactor was turned off and being moved to the second location and while the compactor was running over the pipe 75' from the sensor location. Please note the difference in the vertical axis scaling compared to the case where the compactor was nearby. It was necessary to change scales to make the signal clear.

In the case where there is no signal present, the channels with PZT sensors still exhibit a significant noise floor: about 20 counts peak to peak (Figure 75).

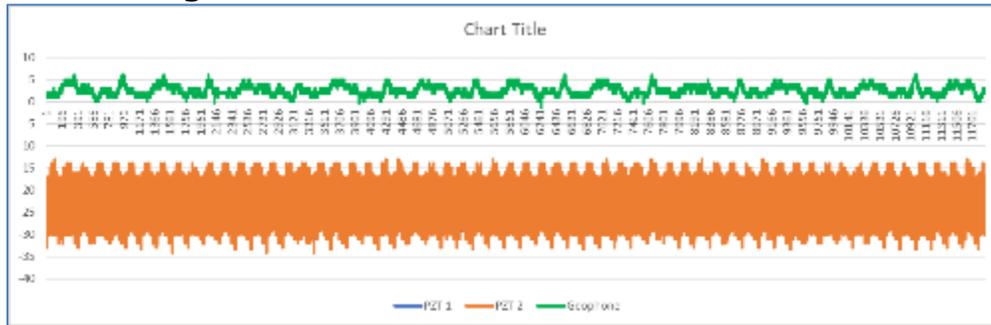
Figure 75: Raw Vibration Noise Floor 15:31:05



Source: GTI

The geophone noise floor is much lower: about three counts. Clearly the geophone demonstrates a superior signal to noise ratio (SNR). When the compactor is activated 75' from the sensors, the geophone does show some response while the vibration sensor responses appears unchanged (Figure 76).

Figure 76: Raw Vibration Data Far 15:31:25



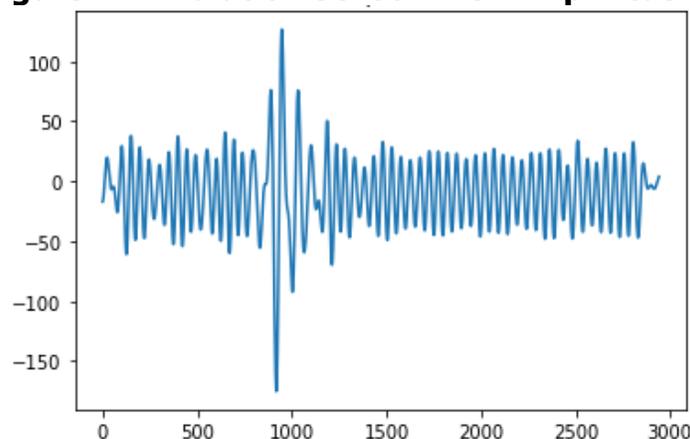
Source: GTI

The introduction of a preamplifier between the vibration sensors and the vibration monitor would both boost the signal level and present a lower impedance to the vibration monitor. This would lower the channel noise that is probably caused by the high impedance of the vibration sensor interacting with the vibration monitor ADC input. Without some such modification, the vibration sensors will not be effective for detecting events in the ROW.

Additional Testing

GTI performed some additional testing outside of this Energy Commission Agreement. This testing consisted of adding an external amplifier between the PZT sensors and the Acellent vibration monitor. The gain of the amplifier was set to 100. The excitation was provided by a 5-pound drop weight striking the surface of the soil near the sensors. This is a much smaller signal input than the compactor or excavator in previous test. Figure 77 shows some data from this testing clearly depicting an impact. This result is very encouraging. It demonstrates that with appropriate amplification and signal conditioning, even small impacts are detectable.

Figure 77: Vibration Sensor with Amplification



Source: GTI

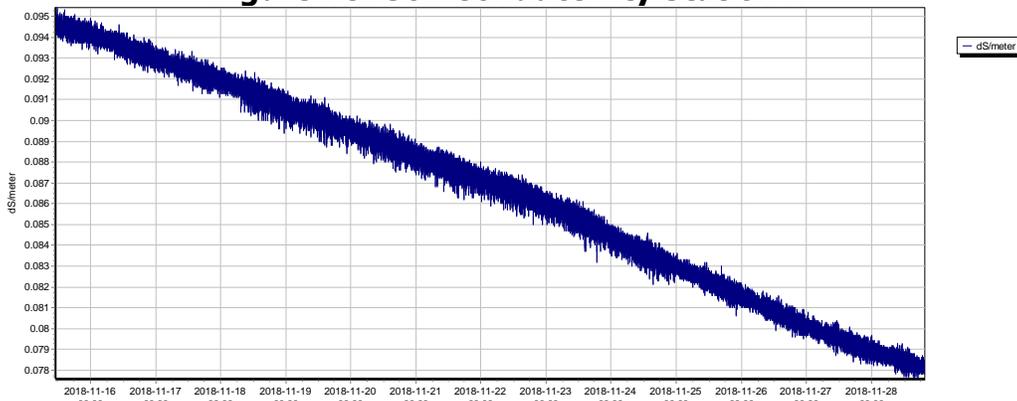
Soil Parameter Measurements

Other factors besides the presence of excavation equipment can affect the integrity of buried infrastructure. Sensors placed in the soil immediately adjacent to the pipe provide information on the immediate environment. Extremes of soil moisture or temperature may represent threats to the pipeline. The soil parameters interact with other measurements such as pipe strain and current density.

Soil Conductivity and Moisture

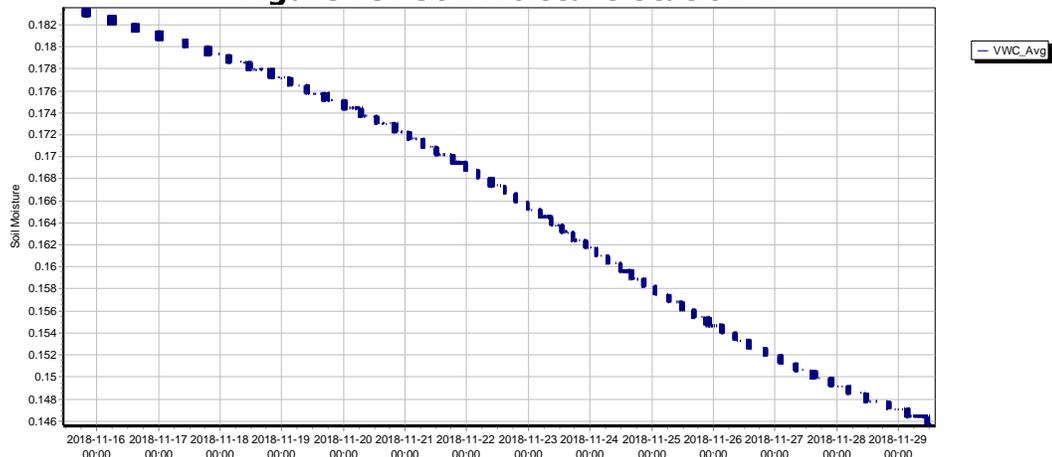
Soil conductivity is measured directly by the sensor; the soil volumetric moisture content is then calculated from the conductivity. The graphs below show the conductivity and moisture over a two-week period (Figure 78 and Figure 79). The conductivity decreases steadily over this time as the soil becomes drier. The "staircase" seen in the soil moisture is due to the calculation precision of the sensor. The trend of decreasing conductivity/moisture is common to all three sensor locations.

Figure 78: Soil Conductivity Station 1



Source: GTI

Figure 79: Soil Moisture Station 1

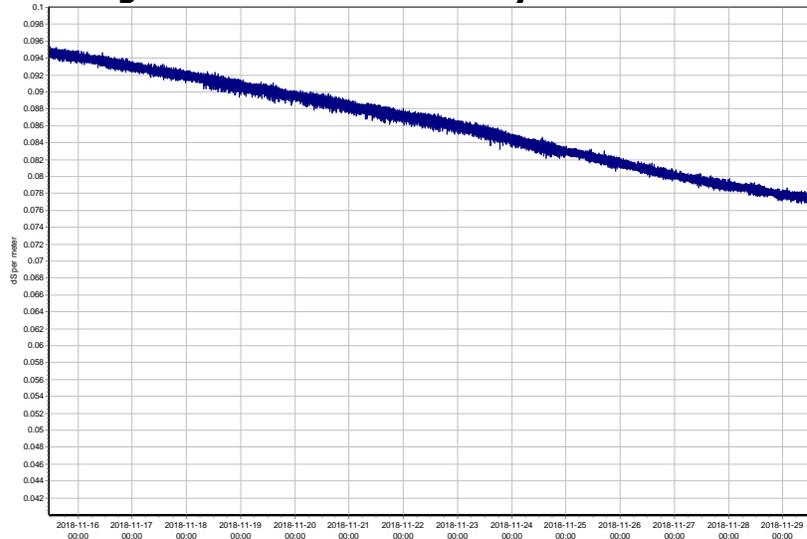


Source: GTI

There are some variations in the magnitude of soil conductivity across the three sensor station locations. Figure 80 and Figure 81 show the soil conductivity at the Station 1 and Station 3 locations plotted to the same scale. While the trend of decreasing conductivity/moisture is the

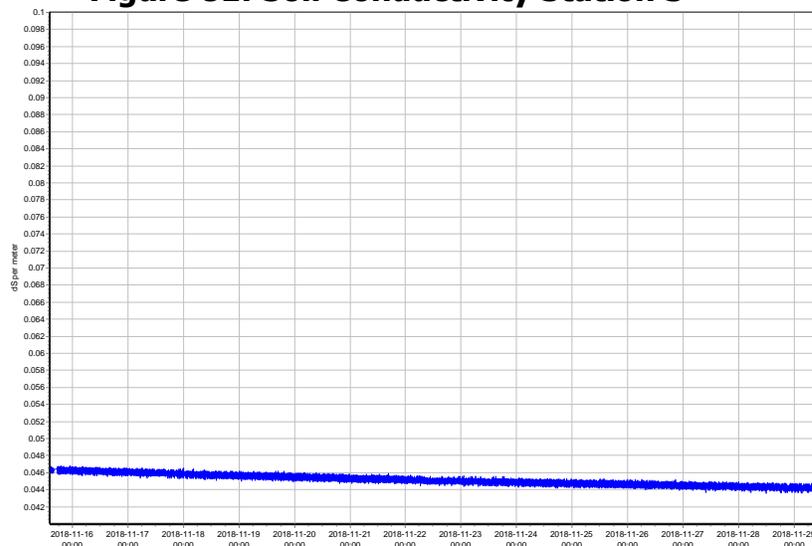
same the magnitudes are significantly different. This difference can be attributed to the size of the excavation and the amount of time it stood open during construction. Station 1 was the smallest of the three excavations. Station 3 was part of a large excavation that involved a pig launcher and multiple valves. This excavation was open for roughly two months longer than the others, giving the soil additional exposure to hot and dry conditions.

Figure 80: Soil Conductivity Station 1



Source: GTI

Figure 81: Soil Conductivity Station 3



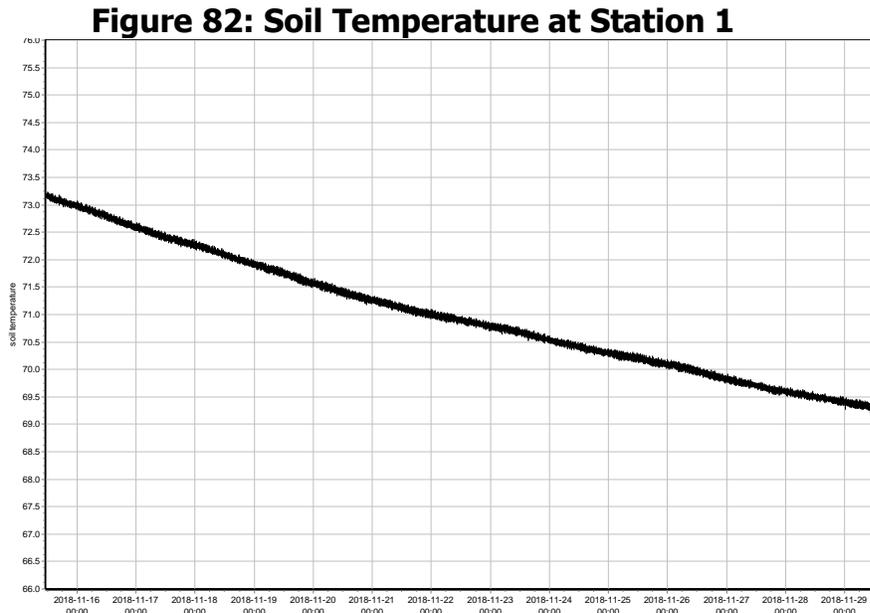
Source: GTI

Soil Temperature

The soil temperature is also measured by the Campbell CS655 sensor. Soil temperature was tracked as it has a direct influence on the pipe strain level. Expansion and contraction of the metal will drive the longitudinal strain level. In the case of extreme low temperatures, an effect known as "frost heave" can occur. If the soil freezes below the pipe level and then

thaws the pipe is subjected to stresses in both directions. A downward force is created as the soil freezes from the top down. The soil will then thaw from the top down exerting an upward force on the pipe. The force is created by the expansion of water in the soil.

Figure 82 shows the seasonal decline in soil temperature at sensor Station 1. The data for Station 2 is nearly identical. In the case of Station 3 the trend is the same, but the values are roughly three degrees Fahrenheit higher for the same period. As noted in the previous section, the Station 3 excavation was open and exposed to direct sun for two months longer than the other two.

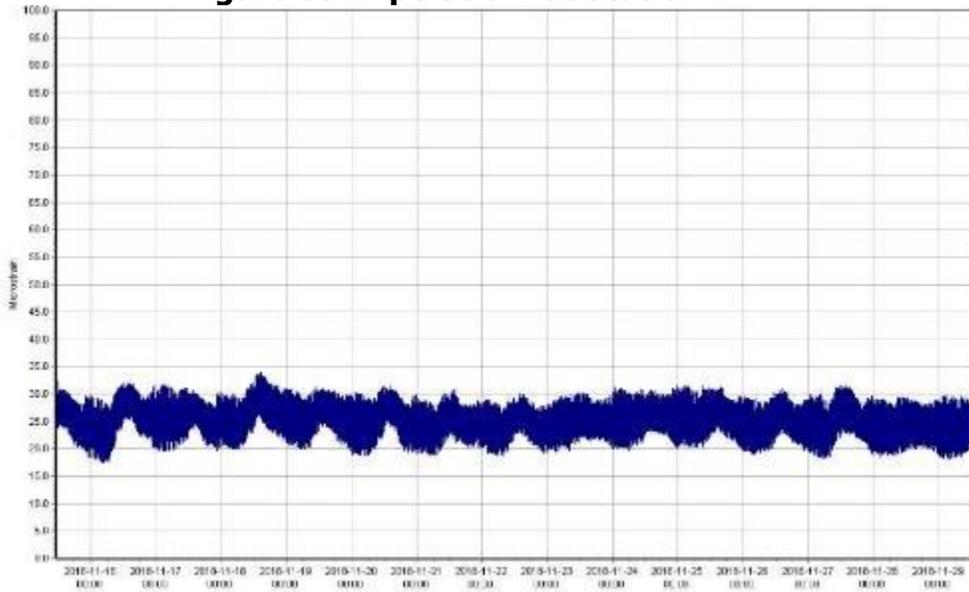


Source: GTI

Pipe Strain Measurements

The pipeline strain level is influenced by several environmental factors. The effect of internal pressure changes on pipe strain during hydro-testing has been covered in earlier reports; changes of up to 200 microstrain were observed. The seasonal soil temperature variation causes the pipe to expand and contract driving the strain level. Figure 83 shows the pipe strain at Station 1 over the same interval as the temperature from the previous section. There is some noise in this plot caused by the proximity of AC power lines that will be discussed in the next section. Additional software filtering in the CR800 can remove these artifacts. There is also a slight downward trend in the strain data that tracks the soil temperature; this is an expected result. This data is typical of all three locations; no unusual strain levels have been observed since baseline data recording has commenced.

Figure 83: Pipe Strain at Station 1



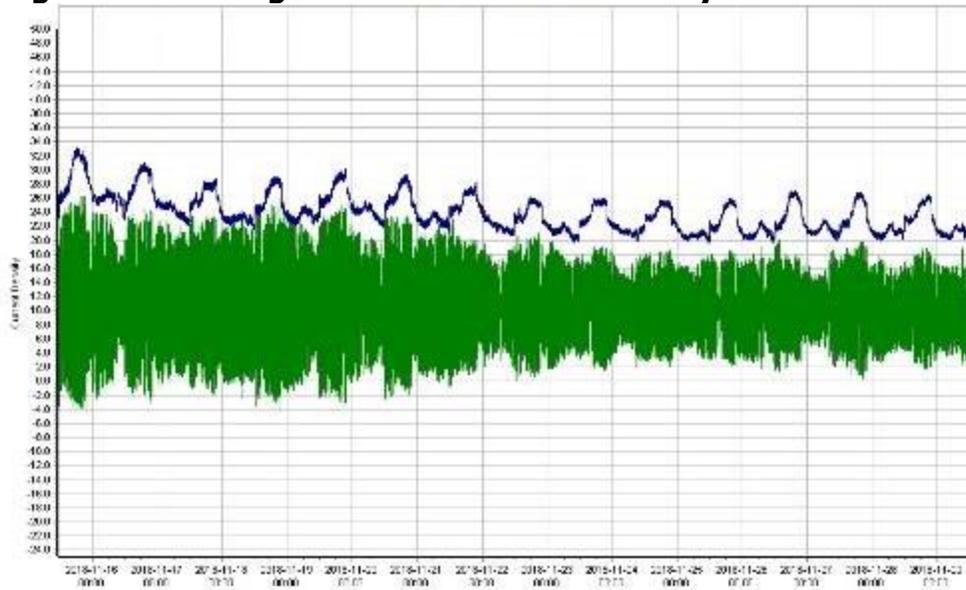
Source: GTI

Current Density Measurements

The pipeline current density measurement provides insight to the effectiveness of the corrosion protection system. This measurement is made using a steel coupon that is buried in the soil. Wires connected to the pipe and coupon are connected through a shunt resistor that allows the current flowing from the soil to the pipeline to be measured. The coupon area serves as simulated break in the coating and measures the amount of current required to protect that area relative to the local soil.

The current density can be resolved into average (or DC) and RMS components (Figure 84). The average, or DC component is an indicator of how well the pipe is protected from corrosion. The RMS value indicates how much AC current may be on the pipe. AC pipeline currents may arise induction from nearby power lines or from direct contact with other buried facilities. In the plot below, the DC component (green trace) does show a reasonable median value but also some noise. The RMS component (blue trace) shows an interesting periodic structure. Both features show a slight downward trend over time. This trend corresponds with the gradual decrease in soil conductivity that was noted in an earlier section. It is relevant to correlate these factors; when conductivity is low the rate at which corrosion may occur is also low.

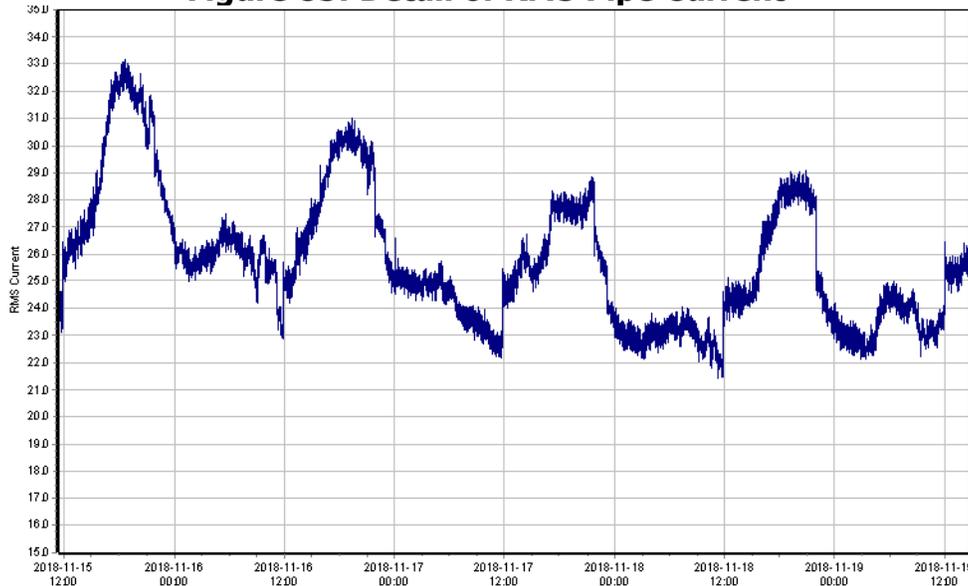
Figure 84: Average and RMS Current Density at Station 1



Source: GTI

What causes the periodic structure in the RMS current? When one expands the RMS feature for closer examination, clearly the period is 24 hours (Figure 85). There is a set of AC power lines that run close, to and parallel with the pipeline. The effect being observed is an AC current induced in the pipeline proportional to the power line current. Looking at the time stamps, the highest values mirror the highest demand for electricity between noon and midnight. There is a corresponding drop in demand after midnight; the cycle repeats daily. This is a reasonable result that has been observed in many other cathodic protection studies.

Figure 85: Detail of RMS Pipe Current



Source: GTI

The current density data at Station 1 and 2 was consistent. Station 3, however has current densities an order of magnitude lower. The reasons for this are still being investigated. As

noted earlier, the soil conductivity at Station 3 is lower than the other two locations given that the excavation was open for a much longer time. This extra drying time for the soil may cause the lower current. The other possibility, again based excavation time, is that the cables were damaged during construction of the other facilities.

CHAPTER 9:

Technology Transfer Activities

There are several avenues for future deployment and commercialization of the ROW monitoring system. However, it's important to note that securing a test site and the initial deployment required considerably more time than planned. The initial technology transfer plans assumed that nine to twelve months of testing on an operating pipeline would be accomplished by the end of the project. This testing would have been presented to several industry forums. Unfortunately, the various delays led to the system testing being compressed into that last three months of the project, which impacted technology transfer activities; the largest impact being that this work has yet to be presented at a public industry forum.

Project Stakeholders

There were multiple stakeholders involved in this work.

- Operations Technology Development (OTD) LLC provided financial support. Some OTD consortium members expressed interest in hosting test sites of the ROW monitor system based on the outcome of this project.
- The U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA) provided financial support. They also agreed to continue their support into 2019 to allow a longer field test to be conducted.
- Leidos Engineering, a project partner, performs installations of private telemetry systems for utilities and other organizations. A successful ROW monitoring system would fit within their normal business model. Again, this will require several additional months of field testing to verify.
- Acellent Technologies, the vibration sensing provider, expressed interest in the utility space as another outlet for their products. Acellent is primarily a provider to the military and aerospace industries currently. The testing experience indicates that their products would need significant re-engineering to be a good fit for pipeline applications.

Industry Exposure

OTD is a consortium research organization consisting of the major natural gas utilities in the continental U.S., plus one member in Canada. As an observer and supporter of this work, OTD has received quarterly reports on the progress. OTD holds bi-annual meetings and has received brief presentations on this work. However, this is not a public gas industry forum; the attendance and circulation is limited to the membership. Several non-California utilities in OTD expressed interest in hosting test sites for this technology, pending the testing results.

DOT PHMSA supports research in improving pipeline safety and has been following this work with some interest. Quarterly reports (coordinated with OTD) were provided to PHMSA along with a public page abstract. These public pages are publicly accessible through their website. The material provided to PHMSA may influence their research allocations for future years and GTI is actively seeking additional PHMSA support for future test sites, some of which will be outside of California.

Utility Feedback

The following are items of feedback that have been received directly from gas utilities:

- Utility 1: We are excited about this technology because it can be installed at discrete points. This makes it appropriate for retrofit applications. Fiber optic systems work but require open trenches over the entire pipe for installation. This is not practical everywhere.
- Utility 2: We need this for agricultural land. Drought and topsoil loss are making pipelines vulnerable to agricultural equipment.
- Utility 3: (non-CA) We are following this as a solution for monitoring in congested urban spaces. Continuous fiber is not practical for us because of the installation issues.

CHAPTER 10:

Benefits to California Ratepayers

Introduction

The pipeline ROW monitoring and notification system will provide important benefits in safety, environmental, and operational areas when deployed. This design approach demonstrated in this project balances economic and practical concerns to provide a reasonable deployment path to capture these benefits. This project demonstrated a ROW monitoring system can be installed and operated effectively and at a reasonable cost.

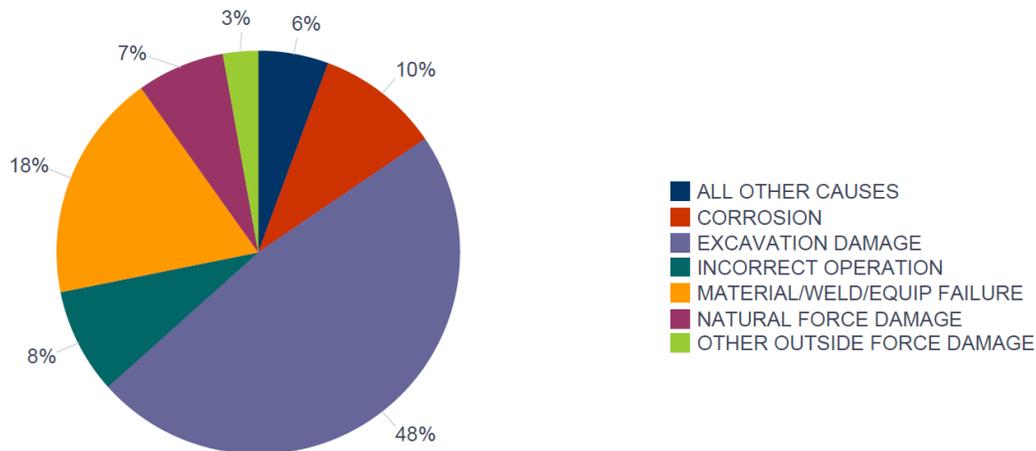
The greatest benefit of ROW monitoring to California ratepayers is improved safety by reducing the risk of incidents from natural gas pipeline damage. This technology provides utility operators the ability to remotely monitor activity in the ROW and the activity of excavation machinery. This provides timely notification to utility operators and assists in the prevention of damage to gas pipelines. Damage that releases gas or impairs the function of the gas delivery system is always undesirable. Any damage carries the risk of escalating into a significant event with fire, explosion, injury, and loss of life. The San Bruno incident in 2010 resulted in 51 injuries and eight fatalities; repair and recovery costs have reached \$639M at this time and may go yet higher.

There are additional benefits in the areas of environment and operational efficiency. Any unplanned release of natural gas from a pipeline has consequences, even if it doesn't ignite. Methane is a potent greenhouse gas; emissions should be minimized to the fullest reasonable extent. Pipeline damage that causes emission must be dealt with immediately and may require a portion of the gas distribution system to be shut down during repairs. The costs of repairs are typically passed through to ratepayers. The costs to the public of greenhouse gas emissions and of energy outages, though less tangible, are still quite real. The following sections attempt to quantify some of these costs.

Background

Figure 86 is the 20-year average of significant California gas transmission line incidents through the end of 2018 (DOT PHMSA). It clearly identifies third-party damage as the largest single source of damage. Outside or natural forces from events such as flooding, or subsidence also cause damage, as does corrosion. The monitoring system designed in this project also addresses these less-common causes. The stationary sensor network can detect activities in the ROW resulting from either excavation activity or outside force. The mobile sensor technology can determine the proximity of excavation machinery to the ROW and so prevent third party damage.

Figure 86: Causes for Significant Pipeline Incidents 1999 to 2018



Source: PHMSA Pipeline Incident 20 Year Trends, <https://www.phmsa.dot.gov/data-and-statistics/pipeline/pipeline-incident-20-year-trends>

The mobile sensor technology has been embodied as the EEN system. This technology was the subject of a separate Commission project, PIR-15-015, and subsequent final report. The benefits of the EEN system are well described in that report and will not be reproduced here.

The stationary monitoring technology described in this report senses vibration levels on the pipeline, tensile strain levels, current density, and soil parameters. These sensed values can be driven by the presence of excavation machinery, by outside force events, or by electrical interference. This provides, for fixed locations, a category of protection not provided by the EEN system which is specific to excavation damage. Are there other technologies that can provide similar types of protection?

There are monitoring systems using a “sensor cable” installed parallel to the entire length of the pipeline being observed. These systems, typically based on fiber optic cable, can be made sensitive to temperature, vibration, and strain. These sensitivities can be used to detect leakage via the cooling caused by escaping gas, the motion of nearby machinery via vibration, and pipe or earth movement via strain. Fiber optic cables are insensitive to electrical interference. The downside to this last item is that fiber optic systems can detect pipeline current or corrosion status.

Installing a continuous sensor cable requires open trench access to the entire pipeline. Trenching is an expensive operation that carries its own set of risks, especially when carried out in populated areas. Let us quantify some of the costs associated with installing such a continuous cable monitoring system.

Trenching cost per foot currently ranges from \$4.40 to \$562 with an average of \$19.52 per foot. Stated another way, the average is \$103,000 per mile with a high value of nearly \$3M per mile. Anecdotally, the authors have heard utility personnel cite costs close to \$10M per mile in urban situations with extreme infrastructure congestion. The costs at the higher end of the range are driven by mitigating the risks and costs associated with trenching. These include avoiding existing infrastructure, traffic control in construction areas, pavement breaking followed by restoration, and maintaining worker safety.

The equipment placed at the end of the fiber optic sensing cable is a fixed cost regardless of the length being monitored. These end devices can range from \$50,000 to \$100,000 depending on the number of parameters being sensed. One end device can monitor between 5 and 15 miles of fiber optic cable. The ability of fiber-based system to locate problems on the pipeline has a resolution of between 3 and 30 feet. The resolution is impacted by the length of the fiber being monitored and by the sensitivity of the end device.

The fiber optic sensing cable itself is the least expensive part of the system. Appropriate fiber sensing cable can be less than a dollar per foot in large quantities. The installation cost is the main driver for the total cost of this type of system, as shown in Table 2. For this example, the average trenching cost per mile was used rather than either extreme.

Table 2: Example of Costs for Continuous Fiber Optic Sensing System

Cost component	5 miles	15 miles	30 miles
Excavation/mile	\$103,000	\$103,000	\$103,000
Fiber/mile	\$1,110	\$1,110	\$1,110
Excavation Cost	\$515,000	\$1,545,000	\$3,090,000
Fiber Cost	\$5,550	\$16,650	\$33,300
End Devices	\$50,000	\$100,000	\$200,000
Total Cost	\$570,550	\$1,661,650	\$3,323,300
Per Mile	\$114,110	\$110,777	\$110,777

Source: Data compiled and collected by GTI from multiple sources

Given open trench construction costs, continuous fiber optic sensing would be a poor choice as a retrofit to existing pipelines. In the case where a new pipeline is being installed, the trenching cost is absorbed by the pipeline work. The incremental cost of adding fiber optic sensing becomes attractive for new construction.

Retrofit Technology

Most California ratepayers live in developed areas with established infrastructure, not conducive to new pipeline construction. There are roughly 214,000 miles of existing gas pipeline currently in California to be considered. High pressure transmission lines account for 12,291 miles of this. The retrofit of a ROW monitor system must be minimally intrusive for both safety and cost considerations. This project recognized these constraints and focused on sensors and equipment that could be installed in small excavations scattered along the pipeline at intervals. It also sought to maximize the distance between installations.

As with open trenches, the cost of a discrete point excavation varies by location. The range of costs per excavation varies from \$850 to \$10,360 with an average value of \$2,950. As with trenching, there are outliers cited by utilities of as much as \$50,000 for a small excavation in extremely congested urban areas.

The current equipment cost for a single stationary installation is roughly \$10,000. The equipment now consists of off-the-shelf modules chosen for quick deployment. There was little attempt at customization for this pilot study. With further development this could be readily be cut to \$5,000. Consolidating data-logging equipment and radios into a single device lowers that hardware cost while simultaneously decreasing the size of the power supply and

enclosure required. To lower costs further, the system would need wide deployment for economy of scale.

The ROW monitor retrofit system does require wireless base stations or “access points”. These are somewhat analogous to the end devices for the fiber optic system. They are fixed cost required to capture data from the stationary equipment and forward to utility operators. The current cost of an access point is \$17,000 and it provides a coverage radius of up to 12 miles.

Table 3 shows example costs for the ROW monitor retrofit system in its current form. The assumptions used to construct the example are conservative. It is assumed that three stationary sensor hardware installations per mile were performed. Based on field data, this provides reasonable sensor coverage. The number of access points was scaled to the pipe mileage such that no sensor installation needs to be at the extreme wireless range of the access point. Finally, the median value for the excavation cost was used rather than an extreme.

Table 3: Example Costs for Discrete Retrofit Monitoring

Cost element	5 miles	15 miles	30 miles
Installations/mile	3	3	3
Excavations Each	\$2,590	\$2,590	\$2,590
Equipment Each	\$9,700	\$9,700	\$9,700
Excavations Total	\$38,850	\$116,550	\$233,100
Equipment Total	\$145,500	\$436,500	\$873,000
Access Point(s)	\$17,000	\$34,000	\$51,000
Total Cost	\$201,350	\$587,050	\$1,157,100
Per Mile Cost	\$40,270	\$39,137	\$38,570

Source: Data compiled and collected by GTI from multiple sources

The example figures demonstrate that the retrofit ROW monitor system, without further optimization, is roughly one-third the cost of a continuous trenched system. If we change both scenarios to the highest excavation cost, discrete or trenched, the demonstrated approach is roughly 98% less expensive (\$63k versus \$2.9M per mile). As stated earlier, no reasonable utility would use open trenches to retrofit a system in an urban area. Discrete excavation is the only viable retrofit approach in developed areas.

Costs Avoided with a Right-of-Way Monitor System

The probable causes of pipeline damage have been shown with the estimated the cost per mile for system that can address these causes. The cost of pipeline incidents that could be mitigated by using a monitoring system were estimated. This discussion limits the focus to California gas transmission lines. These operate at higher pressures than distribution lines and present a correspondingly higher risk.

The stationary ROW monitoring technology developed in this project addresses more than third-party damage indicators. It can detect outside forces by sensing tensile strain changes. Also, by monitoring pipe current density, it can provide indicators of corrosion in progress. We need to point out that stress and corrosion monitoring begin when the system is installed; it cannot detect pre-existing corrosion or absolute stress levels. The current density can only provide insight into external corrosion processes; we will de-rate the ability to detect corrosion

by half to exclude internal corrosion. Some form of baseline data should exist for a pipeline being retrofit with the system to account for pe-existing conditions. Based on these observations, the stationary monitoring system will be able to address 63% of threats to transmission pipeline integrity. The breakdown, based on Figure 86, is given below.

- Excavation Damage – 48%
- Natural Force Damage – 7%
- Other Force Damage – 3%
- Corrosion – 5% (de-rated 10% by half to exclude internal corrosion)
- Total – 63% of threats addressed

Moving on to the costs associated with events, Table 4 provides data on all reported California transmission line incidents from 1999 to 2018 (source: DOT PHMSA). The number of events per year and total are provided. The consequences in terms of fatalities, injuries, and reported monetary cost is also provided. The last row of Table 4 shows 10% of the previous sub-total to show the value of rolling out the system on 10% of transmission lines. The 10% figure is representative of a reasonable deployment rate resulting in a full deployment over 10 years.

Table 4: All Reported Gas Transmission Line Incidents (1999-2018)

Calendar Year	# of Incidents	Fatalities	Injuries	Total Cost as Reported
1999	3	1	1	\$225,000
2000	2	0	0	\$350,000
2001	2	0	0	\$120,000
2002	3	0	1	\$260,000
2003	5	1	1	\$3,753,000
2004	4	0	0	\$230,000
2005	9	0	0	\$3,709,354
2006	5	0	0	\$1,003,000
2007	5	0	0	\$917,500
2008	2	0	0	\$114,300
2009	7	0	0	\$1,960,000
2010	5	8	51	\$559,035,512
2011	6	0	0	\$5,790,500
2012	7	0	0	\$2,658,793
2013	6	0	0	\$2,324,207
2014	13	0	0	\$10,344,591
2015	9	2	15	\$9,633,537
2016	6	0	0	\$2,052,778
2017	10	0	1	\$4,894,255
2018	4	0	0	\$7,762,310
Grand Total	113	12	70	\$617,138,637
63% of Grand Total	71.2	7.6	44.1	\$388,797,341
10% of Subtotal	7.1	0.8	4.4	\$38,879,734

Source: PHMSA Pipeline Incident 20 Year Trends, <https://www.phmsa.dot.gov/data-and-statistics/pipeline/pipeline-incident-20-year-trends>

The possible avoidance of methane release must also be considered. Table 5 is a listing of transmission line incidents that resulted in the release of natural gas given in MCF from 2010 to the present (source: DOT PHMSA). Over this period, a total of 468,501 MCF (thousand cubic feet) was released unintentionally into the environment. Applying the 63% scaler, there is possible 295,156 MCF of greenhouse gas emissions that may have been avoided by a fully deployed system. Adjusting for a 10-year deployment cycle, each year of deployment could lower the emissions by 29,516 MCF.

Table 5: All Transmission Line Incidents Resulting in Gas Release 2010 to 2018

Year	NRC Report #	Unintentional Release	Pipe Diameter	Pipe Wall Thickness	Accident PSIG	Maximum Operating PSIG
2010	950266	63,410	26	0.25	376	400
2010	95380	47,600	30	0.375	386	400
2010	955875	12,000	12	0.281	402	408
2010	960985	8,500	6	0.156	250	650
2011	979566	2,000	16	0.4	360	510
2011	982246	3,270	18	0.25	590	650
2011	989053	1,500	12	0.25	323	350
2011	990236	11	16	0.281	341	450
2012	1030266	51,000	8.625	0.277	318	408
2012	1031956	7,010	12.75	0.25	370	400
2012	1032021	4,700	6	0.156	412	720
2013	1046736	11,300	10	0.25	362	400
2013	1058688	3,000	4	0.225	470	500
2013	106386	13,798	16	0.28	585	600
2013	1066618	1,166	6	0.188	300	313
2014	1089480	27,750	10	0.25	381	400
2014	1092822	1,258	6	0.188	475	500
2014	1099198	92,000	34	0.375	640	757
2014	1101516	36,589	10.75	0.25	640	771
2014	1104165	0	6.625	0.188	380	400
2015	1109328	3,784	10	0.219	264	313
2015	1113940	7,200	12.75	0.25	369	400
2015	1115710	0	3	0.148	236	245
2015	1131545	2,655	6	0.28	118	125
2015	1133387	67,000	34	0.375	660	757
	TOTAL	468,501				

Source: PHMSA Pipeline Incident Flagged Files, <https://www.phmsa.dot.gov/data-and-statistics/pipeline/pipeline-incident-flagged-files>

Deployment Cost Considerations

If, after applying the 63% scaler, the various consequences are divided by the miles of transmission pipe the following values result:

- Monetary cost - \$31,389

- Fatalities – 0.0006
- Injuries – 0.0036
- Methane Emissions – 23.82 MCF

Returning to the cost estimate for the installation of the ROW monitor retrofit system, the cost of the current version is roughly \$39,000 per mile. It would require a modest effort to drop the equipment cost by 50% from the current prototype system. Table 6 shows the impact of dropping the stationary installation hardware cost while holding all else constant. The resulting per mile installation cost (\$24,470) is below the avoided incident cost (\$31,389) per mile. The current investment in the ROW monitoring system is roughly \$2.4 million in development costs from various sponsors. This adds \$194 per mile to the cost of the system.

Table 6: Projected Cost of Next Generation ROW Monitor

Cost	5 miles	15 miles	30 miles
Installations/mile	3	3	3
Excavations Each	\$2,590	\$2,590	\$2,590
Equipment Each	\$5,000	\$5,000	\$5,000
Excavations Total	\$38,850	\$116,550	\$233,100
Equipment Total	\$75,000	\$225,000	\$450,000
Access Point(s)	\$17,000	\$34,000	\$51,000
Total Cost	\$130,850	\$375,550	\$734,100
Per Mile Cost	\$26,170	\$25,037	\$24,470

Source: Data compiled and collected by GTI from multiple sources

Installing a second-generation ROW monitor system on 10% of California gas transmission lines (1,239 miles) would require an investment of \$30,558,696. Other possible benefits resulting from that investment would avoid:

- 0.76 fatalities
- 4.4 injuries
- 29,516 MCF methane emissions
- \$38,879,734 of damages and repairs

With a full 10-year deployment plan, it is very likely economies of scale can drive the hardware costs lower. This will not impact the excavation costs but will provide more margin to install the system in more challenging locations while still maintaining cost effectiveness.

Conclusions

A ROW monitoring system that is too expensive to deploy benefits no one, regardless of how effective it is. By developing technology to retrofit the ROW monitor system one discrete excavation at a time, this project has made it practical for utility operators to use. It can be used when necessary where critical pipelines and population intersect.

In addition to monetary considerations, there are quantifiable societal benefits in terms of avoided harm to humans and to the environment. Utility operators can also realize a benefit in avoided energy outages, emergency response, and the negative publicity associated with these.

CHAPTER 11:

Conclusions and Recommendations

In this research and development project a natural gas pipeline ROW monitoring system was designed, engineered, and tested in the field. Various sensor types were deployed and tested, and the pipeline was hydrotested during the installation period, allowing calibration data to be captured. Support electronics were installed, and a solar power option was successfully demonstrated. The wireless link technology is successful. A total of three sensor stations were installed over a length of roughly 4000' of new pipeline. The system is currently running and providing sensor data. The web hosted user interface is successful. A user interface dashboard was demonstrated that allows visualization of the data from the three sensor stations. Alerts can be generated based on the data received wirelessly. The dashboard is currently running and available to the utility hosting the test site. The following conclusions were drawn from this experience.

Conclusions

The project was not able to run the monitoring system for the originally planned length of time nor at diverse test sites. As noted in the report, the various delays in qualifying acceptable procedure led to only a single test site being acquired. The site that was available is not in a populous area. While it tested the basic hardware, more sites will be needed to test the ability to identify threats to the pipeline amidst background noise. The process to install equipment on utility pipelines is a rigorous one. The rigor is entirely appropriate in terms of safety both for the operators and the public.

Unfortunately, the tested sensors were not able to detect impacts at any significant distance. The performance of the PZT vibration sensors was disappointing. The provider of the equipment had no prior experience in utility application, having come from the aerospace industry, and seemed to lack a grasp of what was needed. The project team believes that piezoelectric vibration sensors can work in this application if proper signal conditioning practices are applied. The additional data captured demonstrates that small impacts are detectable with proper amplification.

The need for low impact installations remains important. Low impact in this context means that the installed equipment is compact and can operate at low power. These attributes have an impact on installation costs that, as was shown in the benefits chapter, is the largest component of the overall system cost. The test system used met these criteria reasonably well for the specific location. The overall size and power will need to be reduced for use in urban areas.

The low impact attribute also extends to the below ground sensor components. The installation of sensors will need to be modified such that the total time required is reduced. This can be achieved by attachment methods that require smaller excavations and less preparation time.

Recommendations and Future Work

Additional work is still needed for further observation and data collection to refine the analytics. It is recommended that the ROW Monitor demonstration now in place be kept in operation. The run time of the current testing has not included any external events that are actionable. Further testing data supported by refined analytics would serve to further disseminate information about this technology opportunity to other utilities in the U.S.

The schedule was driven by the need for installation procedure and utility operator qualifications. Currently, the attachment of sensors can be performed on new pipe prior to commissioning or on pipe taken out of service for maintenance. Once the ROW monitoring and notification system has demonstrated its value to the operators, the qualification of procedures/personnel for installation on live pipes can more easily be achieved.

It is also possible that additional ROW Monitor Systems could be used in follow-on work. For this to take place there are modifications to the existing system that are recommended. The Accellent hardware was not effective at capturing impact data near the pipe and some replacement will be needed before the system is acceptable to utility operators. Once the operators have some level of comfort with the demonstration system, barriers to expanding the demonstration to additional sites will be much lower.

Finally, the current work points out a need for future work on non-invasive sensor technologies for pipelines. Methods of sensing strain or vibration without removing coating or direct metallic contact would be valuable. Significant effort was devoted to assuring that instrumentation in contact with the pipeline does not compromise the existing coating or metal integrity. This limited the amount of data that can be gathered to increase operator awareness of their system status.

Lessons Learned

- The work planning stream for pipeline projects can span multiple years. Get into one project stream early and stay with it. It is not feasible to add this technology to a construction project at the last-minute.
- Work with the project engineers directly to understand their issues. They need to be engaged partners even more so than their management.
- Installation cost is the primary component of the total system cost. Field personnel need minimally intrusive hardware for the ROW Monitor System to see wide deployment.
- Military and aerospace technologies cannot be applied to utility problems without significant modification. Acceptable practices and cost sensitivities are vastly different.
- Wireless and sensing technologies are constantly evolving. Choose providers that have prior experience with utility time scales and expectations.

GLOSSARY AND ACRONYMS

Term	Definition
Acellent	California based provider of condition monitoring sensors; technology based on acoustics and vibration monitoring; currently active in the military and aerospace sector; adapting products to utility applications
AIM	Acellent Impact Monitor, acronym of the passive impact detection software name
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CEC	California Energy Commission, usually called Energy Commission
Compactor	A device for compacting soil by means of a vibrating plate; can be ambiguously referred to as a "tamper" in the sense of tamping down the soil; repeatedly striking the soil to remove voids and increase its density
CPM	Commission Program Manager
DOT	Department of Transportation
GIS	Geographic Information System; database and data viewing technology used by many utilities to track asset locations.
GPS	Global positioning system
GTI	Gas Technology Institute
High Consequence Area	A utility term for areas where pipelines or other infrastructure are close to the public; residential areas in proximity with high pressure supply lines
HLA	High Level Architecture
Hydro-test	The practice of filling a pipeline with pressurized water as a test for leaks; water is incompressible and does not represent a stored energy hazard if there is a rupture; procedure carried out on new pipelines prior to filling them with natural gas
PG&E	Pacific Gas and Electric; company in Northern California
PHMSA	Pipeline Hazardous Material and Safety Administration; department of the Federal DOT with jurisdiction over interstate pipelines
PZT	Material description. Lead Zirconate Titanate is an intermetallic inorganic compound with the chemical formula $Pb[Zr_xTi_{1-x}]O_3$.
RAPID	Real-time active pipeline integrity detection
RAPID+	Real-time active pipeline integrity detection plus

Term	Definition
ROW	Right of Way; a strip or other area of land containing a pipeline held in easement by one or more utility companies; a buffer area on either side of a pipeline where digging or construction is prohibited without permission by utility or utilities within the ROW
RPMA	Random Phase Multiple Access; a radio frequency modulation technique that enables long range data transmission; originally developed by OnRamp Wireless now owned by Trilliant.
SDG&E	San Diego Gas and Electricity; part of SoCalGas; an early adopter of the RPMA wireless technology to read utility meters.
SHM	Structural health monitoring
SMART	Patented "Stanford Multi-Actuation and Receiving Transduction". It is the di-electric polyimide printed circuitry film to host the multiple state sensing piezoelectric sensors for structural health monitoring (SHM) industry
SoCalGas	Southern California Gas Company; utility in Southern California that provided and extensive test site for this work

REFERENCES

- Huebler, James 2006 "Real-Time Acoustic Monitoring of Contact to Pipelines, Phase VII", Gas Research Institute Final Report. GRI-05/0043
- Arnold, John; Todres, Allen; Saha, Narayan; 1984 "Distribution Research Center Task 1: Stresses in Gas Distribution Systems" Gas Research Institute Final Report GRI-86-0183
- Micro Measurements "Strain Gage Applications with M-Bond AE-10, AE-15, and GA-2 Adhesive Systems" Instruction Bulletin B-137 Revision 07-16-14, Vishay Measurements Group, Wendell North Carolina
- Micro Measurements "Surface Preparation for Strain Gage Bonding" Instruction Bulletin B-129-8 Revision 08-07-14, Vishay Measurements Group, Wendell North Carolina
- Campbell Scientific 4/20/15 "Operators Manual for CR-800 Series Dataloggers" Preliminary for OS v.28, Campbell Scientific, Logan Utah